MODEL-DRIVEN MANAGEMENT OF CONSTRUCTION CARBON FOOTPRINT

BY

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THESIS

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ABSTRACT

The construction industry is one of the highest contributors to greenhouse gas emissions and there is an increased awareness towards making the industry more sustainable, efficient and environment-friendly. Although there have been significant strides in building energy efficiency through adoption of rating systems and codes, the focus on developing best practices for reducing the carbon-footprint of the construction phase of the life-cycle of a project has been limited. Although the construction phase is short compared to the use phase of a building, the intensity of emissions during this phase is higher and there is an opportunity for improvement through measuring and monitoring the accrual of carbon-footprint during construction. The research question that this thesis explores is how a Building Information Model (BIM) based workflow used with Life Cycle Assessment (LCA) tools can enable contractors and construction managers to measure and track their carbon-footprint.

To address this research question, the study presents a model-driven framework together with two case studies validating the carbon footprint management tool for the construction projects. Current practice lacks methods to track carbon footprint of the construction phase since the application of Life Cycle Assessment (LCA) methods has remained primarily limited to design and operation phases of a project. In addition, the current methods heavily rely on user inputs on materials and the state of planned-vs.-actual work-in-progress. The presented framework addresses current inefficiencies by leveraging 4D Building Information Models (BIM) in conjunction with LCA tools to benchmark carbon footprint during pre-construction phases and monitor it during the construction phase. The management framework – built on earned value management concepts – offers metrics to assess and communicate deviations between benchmarked and actual carbon footprint, and facilitates root-cause assessments to minimize performance deviations, and excessive carbon footprints.

The two case-studies performed as a proof-of-concept vary in their BIM practices and progress monitoring methods, so a parallel has been drawn between the state of BIM adoption and the opportunity for better carbon-footprint management. The case-studies show that if the framework is used, there is a significant opportunity for reduction in the excess carbon footprint generated at the project level. The deviations are visualized in a timely manner using the BIM-based method which is key to facilitate communication and decision-making for taking required corrective actions. With project teams being able to realize the effect of carbon-footprint, it acts

as an incentivizing force to the upstream supply chain to document and provide embodied carbon data for materials and assemblies used in construction because there is an incentive for the contractors to choose a supplier with lower carbon-footprint. Another application of the proposed management framework is for establishing policies requiring adherence to a carbon footprint budget during project tendering. Also, incentivizing contractors to manage their carbon-footprint by establishing best practices by the implementation of emissions cap-and-trade programs has been suggested and discussed.

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CHAPTER 1: INTRODUCTION

1.1 Overview

The construction industry is one of the top contributors of the greenhouse gas emissions (GHGs), accounting for about 6% of the total United States' industrial GHG emissions, ranking only third after the oil and gas and the chemical manufacturing sector (EPA 2008, 2009). Environmental impacts and hence carbon emissions are considerable at all stages of a building's life-cycle, however the impacts are not well understood and communicated because of the decentralized nature of the construction industry. There has been much recent research and industry push towards sustainability in the building and construction industry but efforts at large have been limited to the energy efficiency of building's operational phase. With an increasingly wide adoption of asset-based rating systems such as LEED, BREEAM, Green Globes and performance-based rating systems such as EPA's Energy Star Portfolio Manager, developers and owners are demanding low-energy and net-zero energy buildings, which shows the importance of sustainable practices in the construction industry.

A typical building life-cycle as defined by UNEP (2009) is shown in the following Figure 1. The life-cycle stages constituting the embodied carbon for a building or infrastructure project, that is in consideration for this study is depicted in the figure. The distribution of the total carbon-footprint across these life cycle stages is shown in the Figure 2, adopted from various benchmarking studies done for assessing the carbon in the supply chain of building construction and from studies by the European Committee for Standardization (CEN) (RICS QS & Construction Standards 2012; Skanska and DC8 2008). Although the construction phase is short (1-2 years) compared to the use phase (40-50 years), the environmental impact of the construction phase is important when aggregated at the national scale (Bilec et al. 2006; Ozcan-Deniz et al. 2012). According to Sharrard et al. (2007) construction energy use accounts for 2.6-

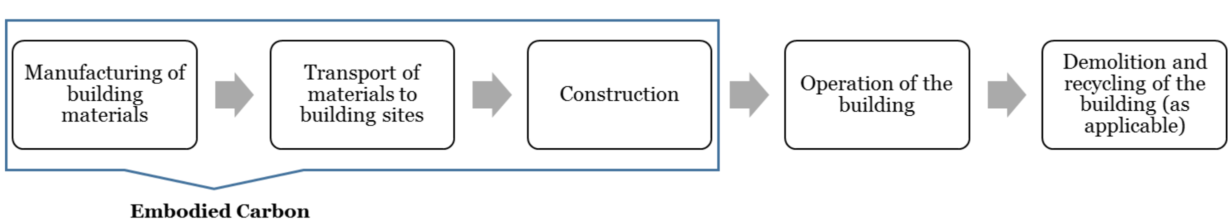


Figure 1. Typical Building Life Cycle Stages

3% of the US's entire energy consumption. Since the construction phase emissions occur over a small time period, the density of emissions is much higher (Ortiz et al. 2009; Sartori and Hestnes 2007) and there is much scope for improvement of construction practices to reduce these impacts.

Several studies have shown that the embodied energy contributes to 10-40% of the energy in the building's life cycle making it the second largest contributor after operating energy (Cabeza et al. 2014; Ramesh et al. 2010; Russell-Smith and Lepech 2011; UNEP 2009; Whitehead et al. 2014). As the buildings become more energy efficient, the contribution of use phase reduces and the construction phase becomes more important to realize the potential of reduction in the overall environmental impacts (Guggemos and Horvath 2006; Memarzadeh and Golparvar‐Fard 2012; Russell-Smith et al. 2015). Figure 3 shows the interrelationship between operating energy and embodied energy for case studies carried out by Winther and Hestnes (1999) which shows that the reduction in energy consumption of buildings usually comes with an increase in the embodied carbon which may be attributed to the materials used in their construction.

Despite its importance, the research on mitigating the effects of embodied energy in

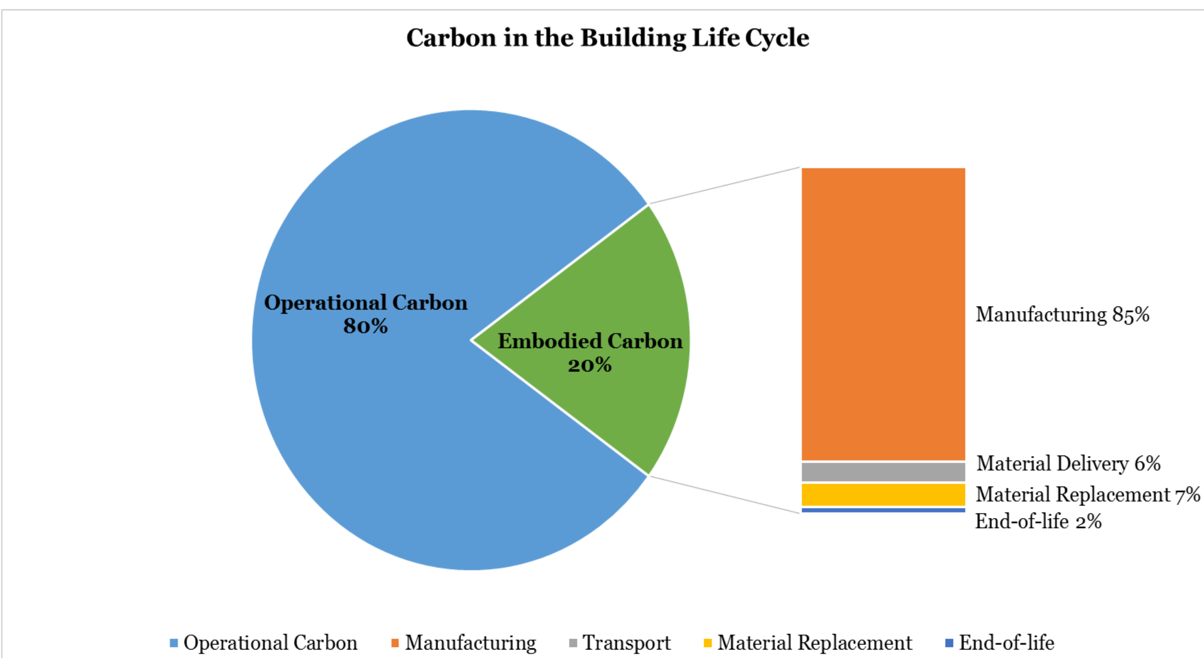


Figure 2. Distribution of carbon over building life-cycle

construction is limited mainly due to lack of environmental data for construction materials;

unavailability of models to track the accrual of carbon footprint over the construction processes and the complex nature of supply chain for construction elements (Guggemos and Horvath 2006).

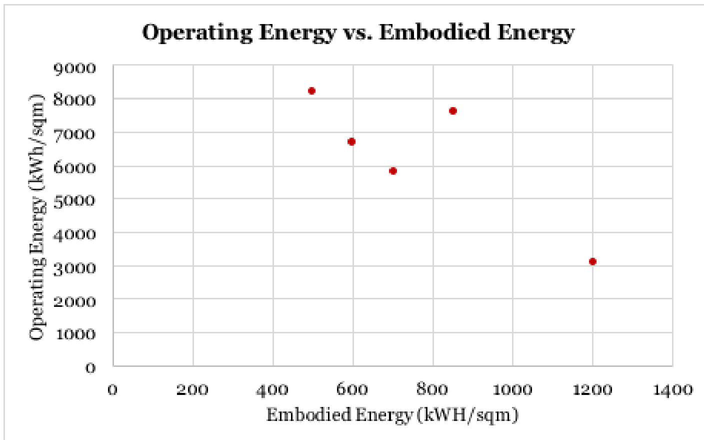


Figure 3. Interplay between embodied and operating energy for case-studies: Adopted from Winther and Hestnes (1999)

Similarly, for civil infrastructure projects such as roads and bridges, the importance of life-cycle embodied carbon is realized since the construction phase is the pre-dominant energy-intensive phase in these projects. Apart from the initial embodied carbon due to construction, most repairs and routine maintenance work is also associated with embodied carbon in these projects. Attempts have been made to quantify the greenhouse gas emissions for highway construction projects using Life Cycle Assessment (LCA) based approaches (Cass and Mukherjee 2011; Mukherjee and Cass 2012; Mukherjee et al. 2013) but these studies do not cover the strategies for mitigation of carbon footprint at the project level. The case-studies in this work are for building projects, but a framework for construction carbon-footprint management would be applicable to infrastructure projects as well.

Market based regulations such as cap-and-trade for controlling emissions generated by different industries are being implemented to help states achieve their carbon-reduction goals. One such example is the cap-and-trade legislation by the State of California which has been a successful program and has resulted in other regulations such as the Off-road regulation for updating and compliance of construction fleet (California Air Resources Board 2011, 2013). Similarly, the overarching plan to reduce the GHG emissions in California to 1990 levels by

2020 endorsed by the Assembly Bill 32 calls for different industries to execute programs for emission reduction and similar response-readiness will be required if such a bill is passed at the national level(California Air Resources Board 2006). Implementation of programs limiting emissions from the construction industry operations asks for shifting the focus to managing the carbon footprint of construction process and demonstrating the compliance to carbon-footprint & emissions targets. One of the Pilot credits for the LEED certification is for Clean Construction, which rewards points for implementing strategies for reducing emissions from construction operations and equipment use. The current LEED v4 rating system rewards credits for Whole Building LCA considerations within the Materials and Resources credits – demonstrating reduced construction carbon footprint can lead to achieving these credits. The impetus for this study was to capture the changing needs of the industry and work on a solution that integrates carbon-footprint monitoring to the current monitoring framework of the project using a BIM (Building Information Model)-based strategy.

Today, construction processes are monitored by highly developed economic cost and schedule controls by means of periodic assessment through earned value management and cash-flow analysis, however there is no monitoring framework to help regulate the release of carbon footprint during the construction phase. Incorporating Life cycle impacts in rating systems such as LEED and BREEAM has resulted in shifting focus towards this problem and construction firms are looking into measuring and minimizing their carbon footprint (BREEAM (Building Research Establishment Environmental Assessment Methodology) 2011; Morrin 2010). Performing life cycle assessments for buildings is more frequent and doable with the availability of material and assembly information in the form of BIM. Several software tools have emerged catering to the need to quantify the environmental impacts of a project by performing whole-building LCAs and generate comparative analyses for design alternatives. Some examples of such tools are Tally, Athena, GaBi and SimaPro which have one or more construction industry specific datasets. The practice of using LCA is still limited to the design phase of projects and its use through the other phases of life-cycle is largely unexplored.

To sum it up, currently there is no integrated method to manage the carbon footprint at the preconstruction and construction stage. In the absence of the transparency that such tools can create, there is little to no incentive for contractors to minimize their impacts during the construction or for suppliers to provide environmental data about their materials. With the use of readily available data from the BIM, the model-driven approach presented here aims to help measure and monitor the carbon-footprint associated with materials during construction and visualizing it in the BIM environment. This will help provide an incentive to the contractors to use the metrics and monitoring tools while not adding to the data collection overhead and result in better decision making to support reduction in carbon-footprint of construction projects.

1.2 Thesis Structure

The organization of work presented in this thesis is as follows:

Chapter 1 introduces the current practices in construction with regard to life cycle assessment in building construction, construction carbon-footprint and significance of research efforts in this area.

Chapter 2 reviews the state-of-the-art approaches to research in - applications of BIM in sustainable construction, Life Cycle Assessment and embodied carbon in construction, integration of BIM and LCA and construction phase carbon footprint monitoring. This review concludes with summarizing the limitations, hence areas of required further research based on the present work.

Chapter 3 presents the research gap and research objectives for this study.

Chapter 4 explains the proposed method in detail. The underlying tools and methods which are the required sub-components for implementing the model-driven management method have been described.

Chapter 5 deals with the validation of the proposed framework by applying it to two real-world case studies performed as a part of this work. The results from the case study are presented through carbon-footprint performance metrics and BIM-based visualization.

Chapter 6 concludes the work with discussion of the results and potential applications for this framework for BIM driven carbon-footprint management. Ideas for future scope and extension of this work have been included towards the end.

CHAPTER 2: RELATED WORK

The literature review for this study is divided into four parts with focus areas on – applications of BIM in sustainable construction, LCA and embodied carbon in construction, integration of BIM and LCA and finally construction phase carbon footprint measurement and monitoring. In the last section, the limitations from current works have been summarized:

2.1 Applications of Building Information Modeling for Sustainable Construction

Green building and BIM are the two major trends that have caught up in the recent times in the construction industry. Despite the wide-spread application, the use of Building Information Modeling (BIM) is still limited to project coordination and visualization and its applications to enhancing sustainable construction have not been fully realized. According to a report by McGraw Hill Construction, only 17% of Green BIM practitioners believe that the use of BIM to achieve their green objectives has been realized at least partly and only 7% Contractor firms report having explored the applicability of BIM for Carbon emission analysis (Bynum et al. 2013; McGraw Hill Construction 2010). Over two-thirds of BIM users predicted moderate to very high growth in use of BIM on LEED projects but agreed that more analysis capabilities would be required for making it valuable which shows an increased market scope for green-practices implementation using BIM (McGraw Hill Construction 2009). There is an increasing trend in use of BIM throughout the project life-cycle through workflows for life-cycle information flow using BIM (Xu et al. 2014). Availability of the right kind of BIM tools to fit the needs of industry for Green BIM applications is one of the factors that may trigger its adoption in the construction phase as well.

A study by Jalaei and Jrade (2014) describes an integration of BIM with green building certification system such that at when at the design stage when alternatives are being compared for energy efficiency, the cost and environmental performance is be estimated together at an early stage. This approach provides a better way to streamline the design of energy-efficient buildings with custom created 3D families for BIM models for materials and assemblies that are linked to both an energy analysis module and a LEED scoring module. The focus of this approach is for the design phase only.

Architecture/Engineering firms have mainly focused on the use of BIM for sustainability applications during the design phase. Comparing alternatives for HVAC design, energy analysis for code compliance and rating systems, daylighting design and lighting analysis are all examples of such analysis. Construction companies also mainly report application of BIM for quantity take-offs, cost estimation and system clash prevention studies (Autodesk 2005; McGraw Hill Construction 2010; Middlebrooks 2005). Although the opportunity for integrating BIM with carbon analysis or accounting is realized (Eddy et al. 2008), the interoperability and usage of BIM with LCA software has not progressed as required and most applications explore the use of external software like SimaPro and Athena for performing LCA (Holness 2008; Stadel et al. 2011). Monitoring and visualizing the environmental impacts of construction is realized as one of the major problems faced by the AEC/FM industry and can improve decision making in the construction for carbon-footprint reduction through better data visualization (Golparvar-Fard et al. 2013).

2.2 LCA and Embodied Carbon in Construction Industry

Life Cycle Assessment (LCA) is defined as a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle (ISO 14040 1997). LCA is being used as a method for improving the sustainability of the construction industry over all the stages of a building life-cycle, with a majority of studies focusing on the operational phase impacts of a project and less focus on construction and the associated embodied carbon (Cabeza et al. 2014; Ortiz et al. 2009).

The development of methodology to use LCA for construction phase has progressed from process based LCA to hybrid LCA models which leverage both process and input-output information to account for the variety in construction process and flows (Bilec et al. 2006, 2010). For infrastructure projects, Cass and Mukherjee (2011) have proposed a hybrid LCA method to quantify construction phase life-cycle inventories and through case-studies concludes that construction equipment use and transportation impact 6-10% of the total construction phase emissions with the rest attributed to material use itself (Mukherjee et al. 2013). A carbon footprint measurement approach for road construction projects by Huang et al. (Huang et al. 2013) incorporates material and transportation impacts in road construction using a greenhouse gas emissions tool called CHANGER. The paper demonstrates the application of LCA based studies to sustainability assessment schemes for construction of infrastructure projects.

The significance of embodied emissions is being realized especially for low-energy and net-zero energy projects where materials contribute to a majority of the emissions and this has been demonstrated in several case studies (Cabeza et al. 2014; Ramesh et al. 2010; Rawlinson and Weight 2007). Dixit et al. (Dixit et al. 2010) analyzed current literature to identify the parameters for developing a consistent database that can be used for embodied energy assessment for construction projects and reports the inherent variations in the parameters that are used for these calculations. Another application of LCA by Ozcan-Deniz et al. (Ozcan-Deniz et al. 2012) shows the use of global warming potential (GWP) values as a parameter in decision making in addition to time and cost during construction by applying multi-objective optimization algorithms to find the optimal construction operations. Importance of life cycle impacts analysis has also been realized for data-centers to incorporate effects of initial and ongoing embodied energy for data center equipment and infrastructure, shifting the focus from just operational energy efficiency through complete life-cycle analyses (Whitehead et al. 2014).

Hammond and Jones (2008) have developed an openly accessible database for embodied energy and carbon emissions for about 200 construction materials. This database is developed from secondary LCA data extracted from literature and LCA studies based on set data quality criteria with most data stemming from the UK. Such databases have the potential for being used to perform embodied carbon analyses and the ideal scenario would be to have the data for a localized geographic region to account for material and electric grid variability with inclusion of several construction materials assemblies.

Use of whole-building LCAs and embodied carbon studies hasn’t gained much momentum because of lack of methods and simple applications to perform these analyses. The recent addition of LCA-based material credits in the LEED v4 rating system and other advanced applications for green building certifications can play an important role to trigger such applications for construction. Moreover, studies dealing with the LCA of material production or embodied energy phases are mostly standalone applications of the life cycle assessment and do not tie into the project’s management framework to influence the decision on what materials to procure at the preconstruction and construction stage (Shiftehfar et al. 2010).

2.3 Integration of BIM and LCA

In this part, the focus was on studying current tools in the industry that provide some integration from BIM data to life cycle and embodied carbon analysis. Software tools like IMPACT by IES and Autodesk Tally aim to integrate some aspects of LCA and BIM to help in design phase decision making by allowing users to quantify the embodied environmental impacts of material and product choices on a whole-building basis (Impact 2014; Tally 2014). IMPACT integrates LCA, Life Cycle Costing (LCC) and BIM to facilitate improvement in design and decision making and it is currently implementable through the IES tool which allows Revit integration through gbXML format export. The gbXML is an open Green Building XML schema that facilitates the transfer of building properties stored in Building Information Models to engineering tools such as energy analysis software. Green Building Studio is another similar tool which uses gbXML or Revit integration to perform energy-analysis on the cloud based platform, but it doesn't include pre-construction or construction phase impacts.

Tally by Autodesk is a promising Revit plug-in tool for LCA of buildings. The most important advantage of Tally is the seamless integration with the BIM which obviates the need to export formats to a third software, and also the model-breakdown structure is preserved and can be navigated within Tally for performing the required analyses. The disadvantage of this tool is the limited variations in the assemblies and the restriction on performing analysis of specific components as was required in this study. The model elements structure has to be followed for all the analysis as well, so it works well for whole-building assessments. Another UK-based tool for measuring and benchmarking construction carbon-footprint called ConstructCO_2 takes into consideration the carbon impacts due to material delivery, daily travel to site, energy use on site, waste generation and operatives to estimate the carbon footprint due to construction activities from usually construction site data.

Apart from these tools, LCA for buildings can be performed in other Life cycle assessment software like Athena, SimaPro and GaBi for which the method generally requires exporting the Bill of materials and mapping the materials to those available in the databases supported by these software (Ramesh et al. 2010). SimaPro comes with the ecoInvent database whereas GaBi has its own construction industry database by thinkstep and PE International. Athena works with the US Life Cycle Inventory (US LCI) database which is open access and the software itself is free to use with a good amount of construction materials and assemblies supported by it. Most of the tools mentioned here do not consider construction-phase impacts, except Athena. To date, the use of these tools from a monitoring perspective throughout the construction of the project has not been demonstrated.

2.4 Construction Phase Carbon Footprint Monitoring

Even though environmental impact assessment models based on LCA for construction processes exist, yet they do not delineate the effects of planning and decision making during the construction at a project level (Ahn et al. 2013; Bilec et al. 2006; Hong et al. 2015; Tang et al. 2013). One of the earlier examples is a study that proposes the integration of life cycle inventory databases with the material information extracted from the BIM for ease of performing LCA. Their work suggests linking crew information to get information about equipment to be used on site and calculating the global warming potential results using the Ecoinvent database (Russell-Smith and Lepech 2011). Tang et al. (2013) used an interactive simulation based method to show the effects of different construction management strategies in controlling GHG emissions from unexpected disruptive events. The emissions under consideration in this study are equipment emissions based on usage hours obtained from manual site data collection. Similarly, other studies focusing on construction operations emissions or carbon analysis rely on manually collected data and ignore the effects of material and supplier selection on the overall construction carbon-footprint (Ahn et al. 2013; Mukherjee and Cass 2012). There is a general agreement in studies on construction stage carbon and emissions monitoring that environmental impacts in terms of GHG emissions or carbon footprint should be included as a third objective in project planning building upon the time-cost tradeoff approach adopted traditionally (Ozcan-Deniz et al. 2012; Tang et al. 2013).

The use of LCA data and integrating earned value analysis with CO_2 monitoring and other models and tools that use LCA to compute the environmental impacts require extensive user input on processes, materials and equipment use (Guggemos and Horvath 2006; Kim et al. 2014). Current studies lack a BIM-driven framework and information about material, processes and equipment usage is to be manually entered in Excel or other formats specified. None of the studies mentioned here address the visualization aspect of carbon-footprint performance which is a key element of the present work. To address these limitations, (Memarzadeh and Golparvar - Fard 2012) presented a method for benchmarking and monitoring carbon footprint via n-dimensional augmented reality models in which the expected and actual released construction carbon-footprint rates were jointly represented in a common 3D environment. Despite progress over the past years, an integrated model-driven framework for estimating, monitoring and controlling emissions is still missing.

2.5 Limitations in the Current Body of Knowledge

From the literature review conducted, the limitations of the work which open up the scope for improvement have been identified in the following areas:

1) Energy and carbon-emissions related studied have typically focused on either the design phase for choosing between design alternatives or on the operation phase for energy consumption related studies. This practice has limited the consideration of environmental impacts to design & use phase and the opportunity for reduction in carbon-footprint through applying embodied carbon studies at the preconstruction and construction stage has been missed. Thus there is no incentive for contractors to use supplier choices and construction strategies that address the carbon-footprint along with the schedule and cost in their bottom line.
2) Studies that exist on life cycle assessment in construction focus on quantifying the equipment emissions only. The two shortcomings of this approach are – i) there is a lack of establishing a causal relationship between changes in the equipment usage and its effect on the project carbon footprint; ii) effect of upstream supply chain such as the material supplier choices have been ignored for managing the construction carbon-footprint
3) There is no significant research in construction carbon-footprint from the monitoring perspective. Development of metrics and methods for visualization of deviations from the baseline or target carbon footprint is not found. Going by what is not measured, is not controlled - in the absence of such metrics and visualization, the aspect of controlling carbon-footprint has remained almost unexplored for the construction phase.

The present study tries to address these areas of limitations identified by proposing the use of a BIM-driven management framework for carbon-footprint. The scope and objectives of the present work is highlighted in the subsequent sections.

CHAPTER 3: RESEARCH GAP AND OBJECTIVES

3.1 Research Gap

It is important to delineate the gap-in-knowledge to clearly define where this study fits in. Based on the study of recent works on the adoption of BIM throughout the project life-cycle, it was clear that work related to use of BIM to enhance the construction sustainability has been left largely unexplored. Also, as BIM-based project monitoring and construction progress analytics are gaining momentum, there is an opportunity to put similar practices in use for measuring and tracking the carbon footprint of projects through construction. The following Figure 4 is a schematic depiction of life-cycle phases of a project and green-BIM adoption practices in these life-cycle stages. The Research Gap delineated in this study for further exploration is the adoption of BIM for sustainability applications in the Construction phase.

3.2 Research Objectives

The overall goal of this study is to create a BIM-driven workflow to measure and manage construction carbon footprint which would result in incentivizing contractors and construction managers to regulate their environmental impacts. The BIM-driven method is important because

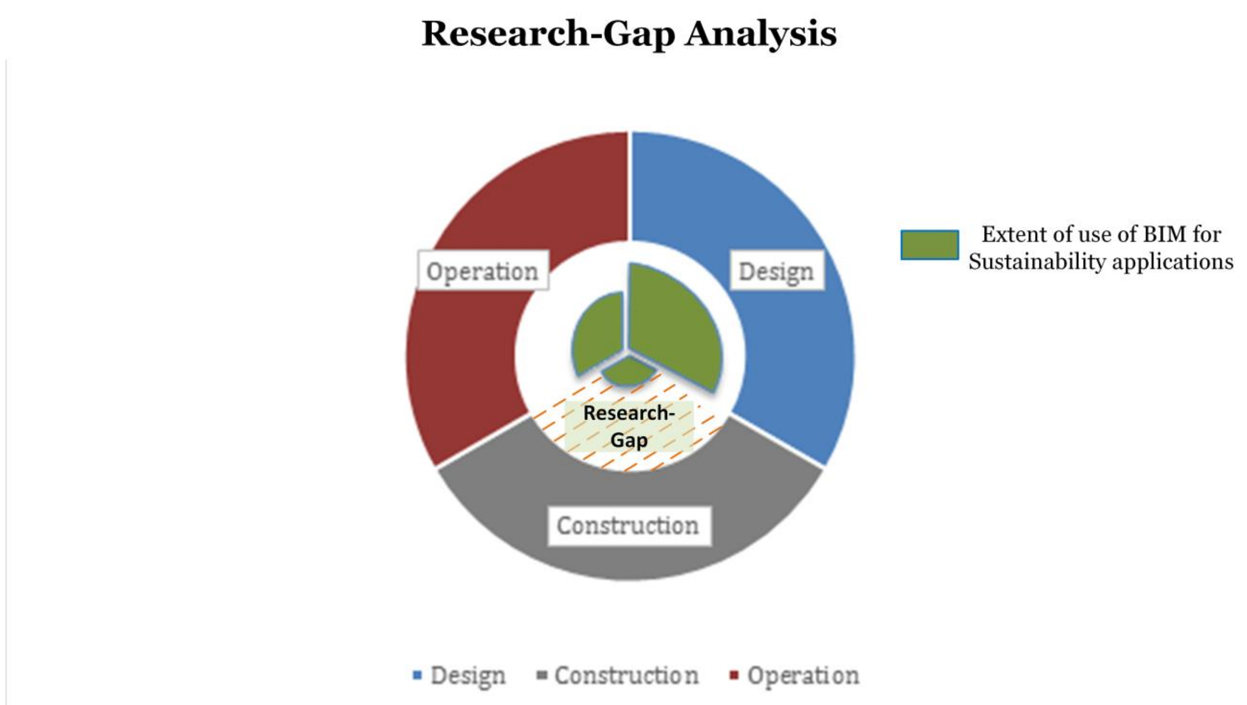


Figure 4. Schematic figure representing the Research-Gap for the study

it leverages the existing information in the form of models and the project's monitoring framework without requiring much additional effort for data collection. The validation of such a workflow through case-studies is another key aspect of the research because it sets the basis for the possibility of automating this process. It is also to demonstrate the applicability of the model for implementing cap-and-trade programs for controlling project emissions in construction since having the required data for actual carbon is essential to realizing the deviations for these programs. Based on the research-gap and the scope envisioned for this work, the following research objectives have been defined:

i. Develop a BIM-driven framework to measure construction carbon-footprint
ii. Develop an earned-value analysis based method to evaluate deviations in carbon footprint performance with the help of carbon-footprint monitoring metrics suggested in this study
iii. Suggest a visualization approach to represent carbon-footprint performance deviations at work-package level which helps contractors to take timely corrective actions
iv. Validate the framework by applying it for real-world projects as proof-of-concept case-studies
v. Evaluate the applicability of the BIM-driven method and discuss the applications with respect to current rating systems and possible carbon-cap programs

The study tries to address these objectives and present results and suggestions for the same.

CHAPTER 4: PROPOSED METHOD

For the BIM-driven carbon footprint management method, this research builds upon the originally developed framework by Memarzadeh and Golparvar-Fard (2012). The thesis introduces a preliminary n-dimensional augmented reality method for representing expected vs. actual carbon-footprint in a 3D model. Along with refining the metrics, the method is expanded upon in this work and different BIM and LCA tools have been used for the two case studies that were conducted. The visualization method is also modified to suit the current practices in a better way based on the case-studies conducted.

4.1 Method Overview

The method accounts for carbon-footprint at the pre-construction and construction phase. The energy consumption during the use phase and the end-of-life phase are not considered. The proposed BIM-driven method to monitor and manage the carbon footprint is divided into two parts: (a) model-driven measurement of material carbon footprint and (b) a monitoring and management framework for construction carbon footprint. The following Figure 5 represents the data used for implementing this method. Most of this data is available from the project for its progress monitoring framework and there isn't any need for additional data collection. The more robust and developed the BIM and virtual construction practices for a project, the easier it is to use existing data to perform this analysis for carbon-footprint.

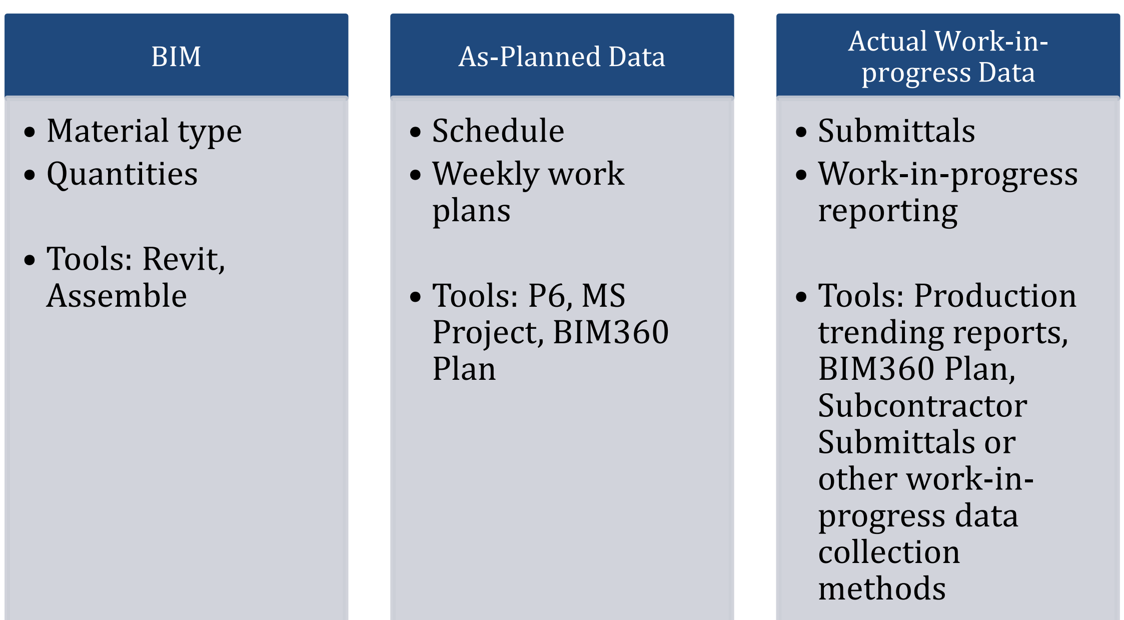


Figure 5. Data collection and tools for implementation of the framework

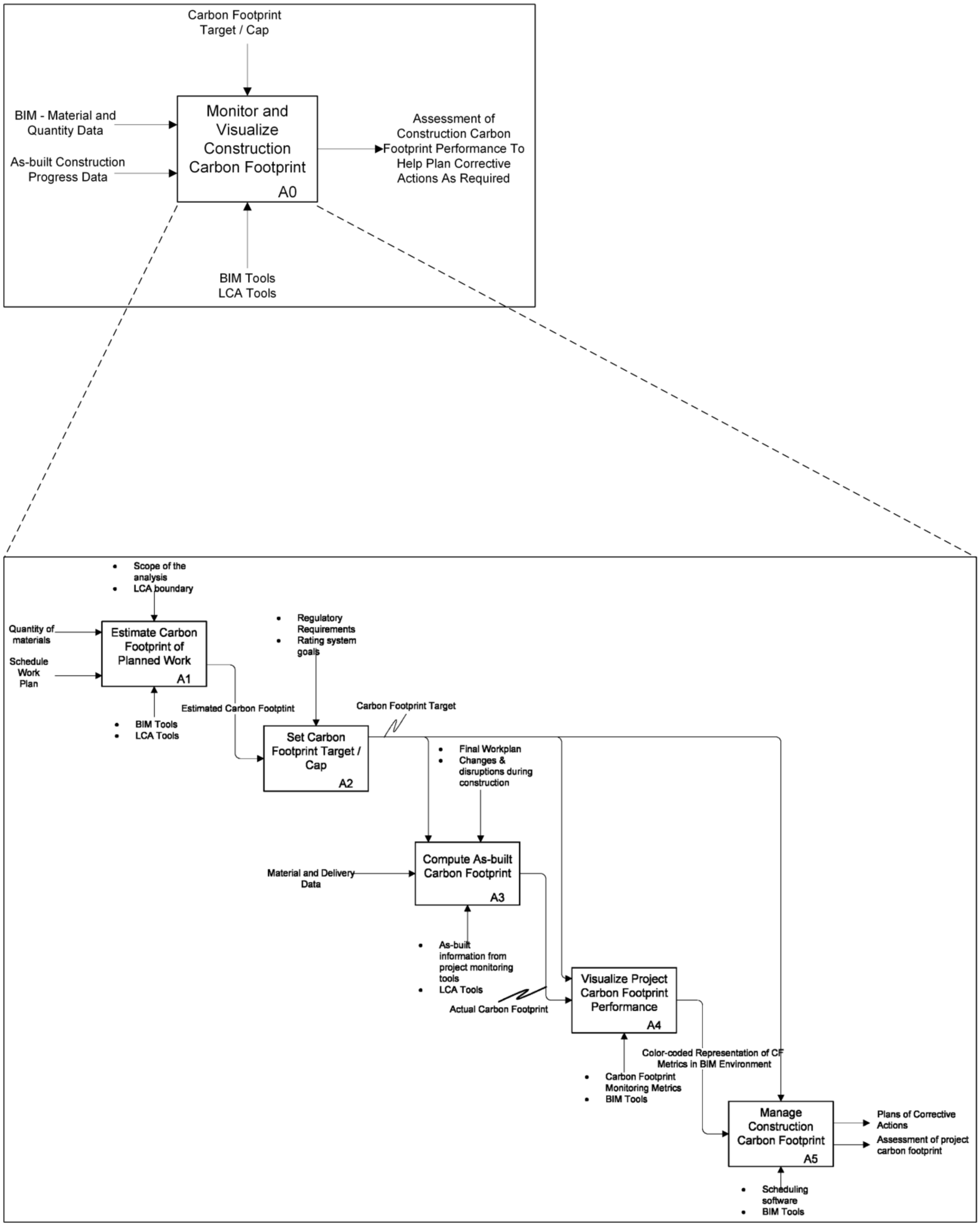


Figure 6. IDEF0 model for the proposed BIM-driven Carbon Footprint Management Framework

The overall framework for carbon-footprint management comprises of three stages:

- Estimating or benchmarking the baseline carbon-footprint
- Assessing the actual carbon-footprint released
- Visualizing the deviations in BIM environment and taking corrective actions

In general, the benchmarking phase deals with calculating an estimated carbon footprint value for the work-as-planned based on the quantity and scheduled work for the project. As shown in Figure 5, the BIM and the schedule for the project are the major data sources for this stage. It also includes setting a baseline carbon emissions value as a target for the project taking into consideration the regulations and rating systems compliance requirements if any. The actual construction progress information from the submittals and work-in-progress monitoring of the project is used to calculate the actual amount of released carbon-footprint. At both these stages the LCA tool along with emission factors for fuel use due to transportation of materials is used for calculating the Carbon-footprint values from the given quantities of materials. An important point to be noted here is that this carbon footprint is measured at the preconstruction stage to be set as a baseline or benchmarked value. As the construction progresses, the actual carbon footprint values are measured using the same method as explained in detail in the section 4.3.

To assess the performance of the project, the actual carbon footprint is compared with the baseline using metrics and methods defined in this study. The carbon-footprint monitoring metrics are based on the earned value management method to analyze the project carbon-footprint performance. In the visualization stage, the deviations in the planned and actual carbon-footprint are represented with the help of color-coding in the BIM environment. This visual representation enables stakeholders to realize the performance quickly and take required corrective actions to comply with the carbon target set in the first stage.

To detail this framework, an IDEF0 functional model has been created which represents all key elements of the method and the inputs, outputs, controls and tools for each of the processes in the model. The Figure 6 above shows the top level context diagram and its decomposition for the carbon-footprint management model. A similar functional modeling approach is seen in Ahn et al. (2013) for estimating and monitoring of pollutant emissions from construction equipment operations.

The underlying methods and concepts for each of the processes in the model have been described in detail in the subsequent sections.

4.2 Life Cycle Assessment Methodology and Tools

4.2.1. Life Cycle Assessment (LCA)

Life cycle assessment or LCA as it is generally referred to as, is one of the most widely used methods to quantify the environmental impacts of products and processes with applications across industries. The entire life cycle of a product may include raw material extraction, manufacturing, transport, construction, operations and end of life. The scope and boundary conditions for LCA are defined based on the goals of the analysis and problem that is to be addressed (NREL 2015; UNEP 2015). In order to understand the methodology used to compute the carbon-footprint for this study, it is important to clearly define the system boundaries for the life-cycle assessment and the resulting inventory and impacts that are being considered. The boundary conditions used in manufacturing industry for performing LCA analyses is usually defined as cradle-to-gate, cradle-to-grave or cradle-to-cradle. A custom boundary definition has been defined for computing the LCA derived embodied carbon for the construction materials which is called *cradle-to-site*. *Cradle-to-site* emissions are defined as cradle-to-gate emissions with the addition of emissions due to delivery to the construction or installation site as described in RICS QS & Construction Standards (2012).

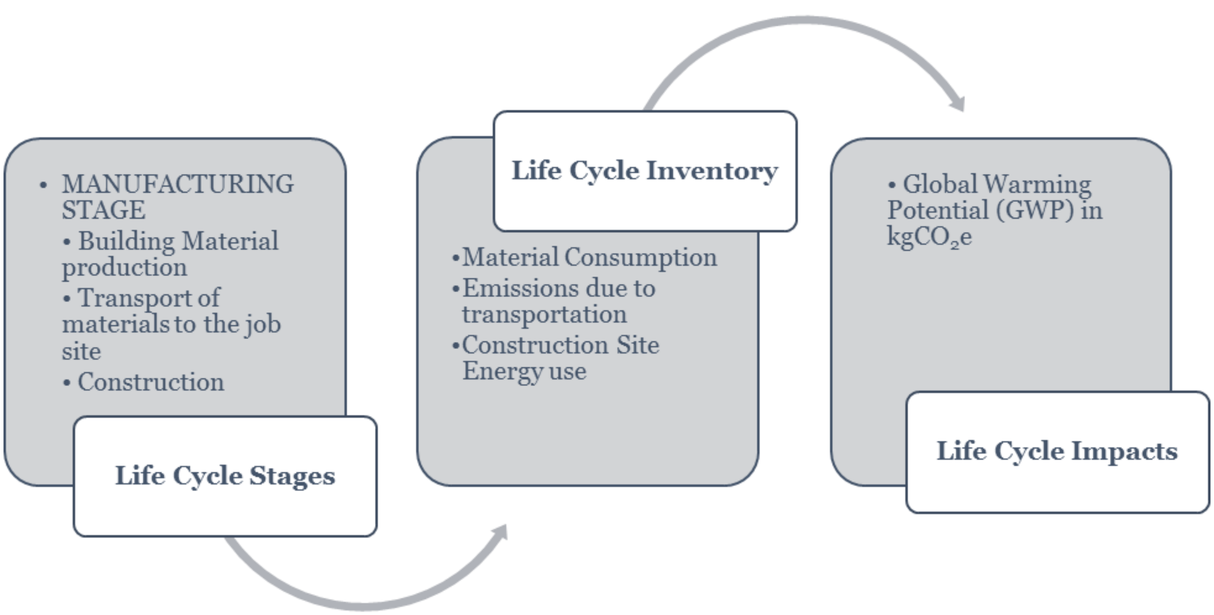


Figure 7. Life cycle assessment boundaries, inventory and impacts

The term ‘embodied carbon’ refers to the lifecycle greenhouse gas emissions (expressed as carbon dioxide equivalents – CO_2e) that occur during the manufacture and transport of construction materials and components, as well as the construction process itself and end-of-life aspects of the building. In literature, the term ‘embodied carbon’ of construction materials and products is sometimes used interchangeably with the term ‘carbon footprint’. An embodied carbon or carbon footprint assessment is a subset of most LCA studies. For this study, the life cycle impact results in terms of TRACI impact categories for Global Warming Potential values have been used – which essentially is the carbon footprint.

Figure 7 shows the life cycle stages under consideration with the corresponding inventory and impacts associated. This is an overview of the LCA model that is being implemented with data collection using BIM and analysis using LCA tools in this study.

4.2.2. LCA Tools

The use of different LCA databases and tools was explored for this study. They are described briefly here.

Hammond and Jones database:

The Hammond and Jones database is an open-access database also known as the Inventory of Carbon and energy database by the University of Bath. This database has been used in the previous studies by Memarzadeh and Golparvar-Fard (2012) and Taveras (2014). It contains almost 200 different materials for which the embodied energy and carbon emissions data has been extracted from peer-reviewed literature. The database is primarily focusing on UK construction but has certain provisions for worldwide application as well (Hammond and Jones 2008). Since it doesn’t have US specific manufacturing data, it was not used for the calculations in this mehtod. One of the goals of this study is to push the suppliers to provide environmental data for their products – which is why using local data was preferred.

Tally:

As introduced in the literature review, Tally is an Autodesk product, functioning as a plug-in for Revit used for performing LCA within the Revit environment. The most important advantage of Tally is the seamless integration with the BIM which obviates the need to export formats to a third software. The model-breakdown structure is preserved and can be navigated within Tally for performing the required analyses, i.e. the elements or assemblies need to be chosen. The disadvantage of this tool is the limited variations in the assemblies and the restriction on performing analysis of specific components as was required in this study. Since it is divided as the model's structure, it has to be followed for analysis as well which means the analysis for specific locations or work-packages based on the work-plan cannot be conducted. Reports generated from Tally provide a good breakdown of relative impacts of different materials in the overall life cycle impact of.

GaBi:

GaBi is a commercial product LCA tool, which works on a process-based LCA model. Its product database is developed through industry reviews and technical literature and it also has some life-cycle cost analysis capabilities. The databases in GaBi include one for Building materials and the tool is available for a cost.

Athena:

Athena Impact Estimator (IE) is a freely available whole-building design decision support tool. This tool is mostly constrained to structural components and gives flexibility to the users to add materials (Cabeza et al. 2014; Whitehead et al. 2014). It also has the capability to enter use-phase impacts exported from analyses carried out in Energy analysis tools. The Impact Estimator (IE) provides options for creation of a project – the user can either enter building information or import a Bill of Materials generated from BIM and 3D modeling tools (Athena 2013). For this study, this feature was very helpful because it provided with the flexibility and interoperability to conduct assessments directly off of Bill of Materials generated from the Revit models and other BIM tools such as Assemble. The quantities for which the analysis is performed depends on the work planned and actual work at the different stages during pre-construction and monitoring of the project.

The impact results from the IE are categorized into the main life-cycle stages including product manufacturing, transport, on-site construction, use, end-of-life and benefits and loads beyond building life. The manufacturing stage impacts have been used to account for the embodied carbon footprint of the materials which includes raw material extraction, transport of raw materials up to manufacturing plant and manufacture of the products. Another important advantage of Athena IE is that it is based on a North American database taking into consideration manufacturing technology, transportation and electricity grid differences as well as recycled content differences for products produced in various regions.

Although the IE also has the information supporting the processes of transportation of material and equipment to the site, this information is based on transportation distances based on North American averages (Athena Sustainable Materials Institute 2014a; b). This present study aims to envision the effects of material supplier choices based on project and site-specific scenarios – so the transportation stage impacts are computed based on actual supplier distances from the job site. The file-interchange workflow using Athena is really simple and has been implemented for both the case-studies in this research.

4.3 Model-Driven Measurement of Material Carbon Footprint

As explained in the LCA methodology, the total carbon footprint under consideration here is the cradle-to-site carbon footprint. This cradle-to-site embodied carbon is denoted as E_{cs} in this study and can be calculated using the embodied carbon of the material associated with the manufacturing of the material and its transport to site as follows:

$$E_{cs} = E_{cg}(\text{cradle} - \text{to} - \text{gate}) + E_{gs}(\text{gate} - \text{to} - \text{site}) \qquad (1)$$

Where E_{cs} is the *cradle-to-site* embodied carbon

E_{cg} is the *cradle-to-gate* embodied carbon, i.e. Manufacturing of the material

E_{gs} is the *gate-to-site* embodied carbon., i.e. carbon footprint due to transportation of the material to the job site

4.3.1. Manufacturing Carbon Footprint (cradle-to-gate)

Athena Impact Estimator as stated previously, is a whole building impact estimation tool used to calculate the embodied carbon in this study. Athena has a capability to import Bill of materials from any CAD program and over 1,200 structural and envelope assembly combinations can be modeled in its environment. The environmental impact reports generated from Athena are consistent with the TRACI impact categories (Athena 2013). For this method, only the Global Warming Potential impact category for the product manufacturing stage is used which results in the kg CO_2 equivalent (kgCO_2e) emissions for the material or assembly under consideration. The product manufacturing stage accounts for the cradle-to-gate embodied carbon (E_{cg}). As described in the LCA tools, the manufacturing stage in IE is comprised of impacts from raw material extraction, transportation of the raw materials and the manufacture of the product or assembly.

The main steps in the procedure of using the Impact Estimator for computing the carbon-footprint of materials is shown in the below Figures – Figure 8 shows the creation of a new project in IE interface. Basic information such as the building height, life expectancy and gross area along with the building type and location is to be entered at this stage. There are three ways

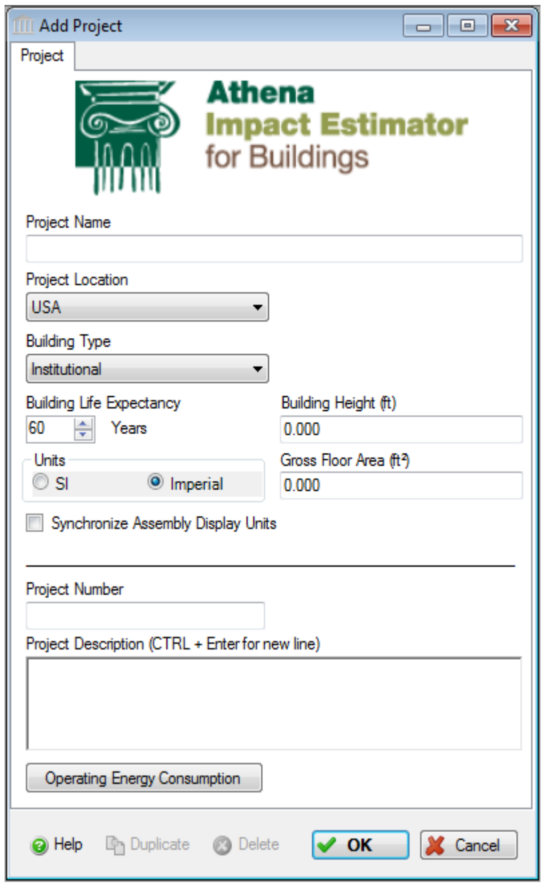


Figure 8. Screenshot showing addition of general project information using Athena Impact Estimator for creating a new project

to add materials under consideration for the impacts calculation. We can create assemblies manually or add extra basic materials which allows the flexibility to choose different variations of the materials. The third way is to import Bill of Materials from a BIM program. For the development of our case studies, we used the direct import of the Bill of Materials from Revit files or other BIM platforms such as Assemble for the quantities of material. The step for Bill of Materials import is shown in the Figure 9. Once the file is imported, one needs to map the materials to the closest available alternatives in the database.

The final step is to generate the required analyses in the form of reports which is shown in the Figure 10. The reports can be generated for the life cycle impacts per life cycle stage and also based on embodied effects by assembly groups. The life cycle stage based reports were generated for this study. This report gives information about the Global Warming Potential (GWP) impacts in terms of kgCO2e per life-cycle stage from which, as explained in the LCA methodology, the Product Manufacturing stage impacts have been used for the study. The reports appear as follows, shown in Figure 11. The red box marked on the Figure 11 highlights the information used from the report for the embodied carbon footprint calculation for cradle-to-gate boundary condition E_{cg}. The report can be obtained in PDF, Word and Excel formats, and for the ease of interoperability, the Excel format has been used to perform further analysis and calculations.

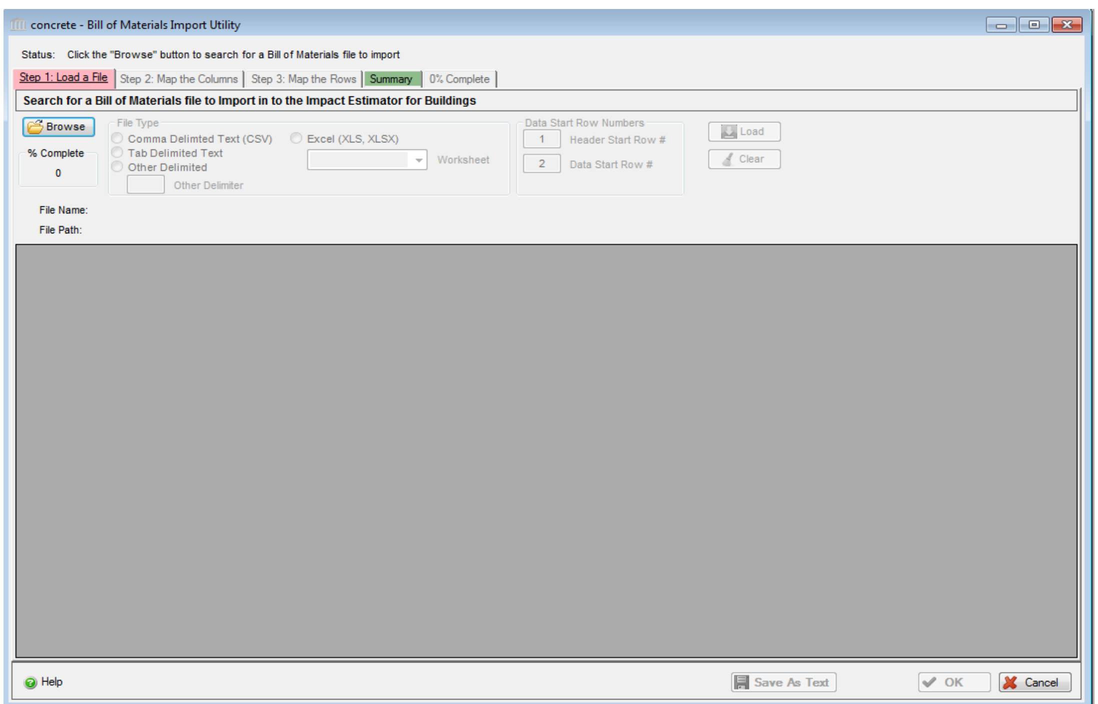


Figure 9. Screenshot showing Bill of materials import utility for IE

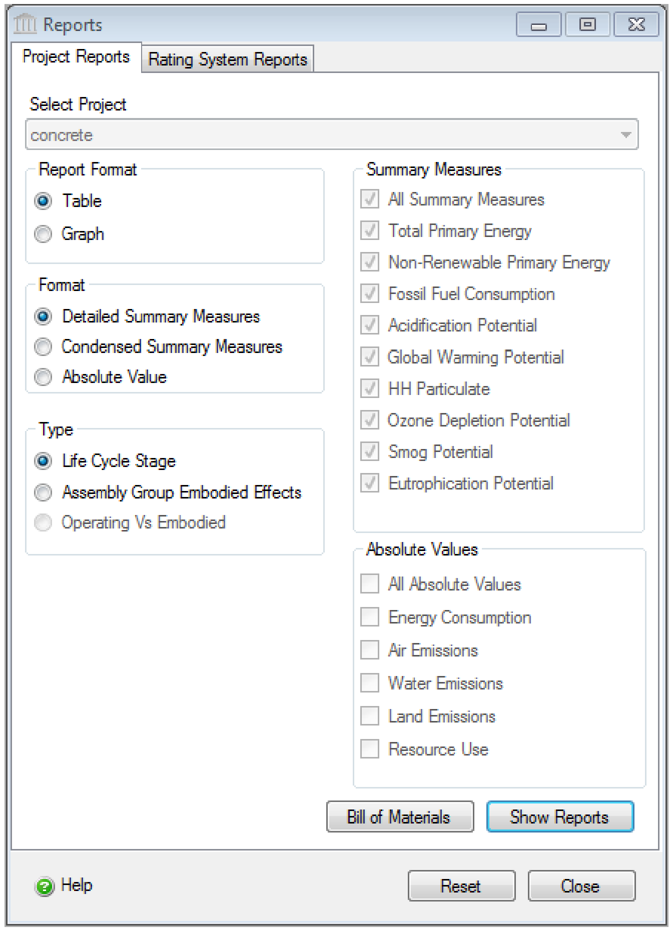


Figure 10. Screenshot showing generation of Reports in IE

		PRODUCT (A1 to A3)			CONSTRUCTION PROCESS (A4 & A5)			USE (B2, B4 & B6)				END OF LIFE (C1 to C4)			BEYOND BUILDING LIFE (D)			TOTAL EFFECTS	
Summary Measure	Unit	Manufacturing	Transport	Total	Construction-Installation Process	Transport	Total	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	Total	De-construction, Demolition, Disposal & Waste Processing	Transport	Total	BBL Material	BBL Transport	Total	A to C	A to D
Global Warming Potential	kg CO2 eq	4.13E+05	1.92E+04	4.32E+05	3.59E+04	1.92E+04	5.52E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.76E+04	9.05E+03	2.67E+04	0.00E+00	0.00E+00	0.00E+00	5.14E+05	5.14E+05
Acidification Potential	kg SO2 eq	1.90E+03	1.78E+02	2.08E+03	2.99E+02	1.74E+02	4.73E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.36E+02	8.16E+01	3.17E+02	0.00E+00	0.00E+00	0.00E+00	2.87E+03	2.87E+03
HH Particulate	kg PM2.5 eq	8.78E+02	1.04E+01	8.89E+02	4.93E+01	1.04E+01	5.97E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.17E+00	4.90E+00	1.11E+01	0.00E+00	0.00E+00	0.00E+00	9.59E+02	9.59E+02
Eutrophication Potential	kg N eq	4.47E+01	1.22E+01	5.68E+01	1.59E+01	1.19E+01	2.77E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.57E+01	5.58E+00	2.13E+01	0.00E+00	0.00E+00	0.00E+00	1.06E+02	1.06E+02
Ozone Depletion Potential	kg CFC-11 eq	4.35E-03	7.01E-07	4.35E-03	2.18E-04	6.90E-07	2.19E-04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	7.67E-07	3.24E-07	1.09E-06	0.00E+00	0.00E+00	0.00E+00	4.57E-03	4.57E-03
Smog Potential	kg O3 eq	2.27E+04	6.19E+03	2.89E+04	8.39E+03	6.03E+03	1.44E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00	8.36E+03	2.83E+03	1.12E+04	0.00E+00	0.00E+00	0.00E+00	5.45E+04	5.45E+04
Total Primary Energy	MJ	3.05E+06	2.48E+05	3.30E+06	3.80E+05	2.35E+05	6.15E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.62E+05	1.10E+05	3.72E+05	0.00E+00	0.00E+00	0.00E+00	4.29E+06	4.29E+06
Non-Renewable Energy	MJ	3.02E+06	2.48E+05	3.27E+06	3.78E+05	2.35E+05	6.13E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.62E+05	1.10E+05	3.72E+05	0.00E+00	0.00E+00	0.00E+00	4.26E+06	4.26E+06
Fossil Fuel Consumption	MJ	2.93E+06	2.48E+05	3.18E+06	3.73E+05	2.35E+05	6.08E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	2.61E+05	1.10E+05	3.71E+05	0.00E+00	0.00E+00	0.00E+00	4.16E+06	4.16E+06

Figure 11. Screenshot of a life cycle impacts report by Life-cycle stage from IE

4.3.2. Transportation Carbon Footprint (gate-to-site)

The emissions due the transportation of the materials from the supplier to the construction site are calculated using the carbon footprint associated with the fuel usage of the delivery trucks based on standard mileage information about the vehicle. The equivalent carbon emissions from the combustion of a gallon of gasoline is the product of the quantity of the fuel use and the carbon emission factors. This accounts for the *gate-to-site* emissions (E_{gs}) for the given materials. The material transportation data should be easily available from the suppliers or can be estimated based on the quantities of the material and average vehicle capacity. For concrete, the National Ready-Mix Concrete Association (NRMCA) provides data on the fuel consumption and capacity of trucks through an industry-wide fleet benchmarking and costs survey which is published in the form of a report (Hinkle et al. 2014). This report was used to obtain information about vehicle capacity and mileage for concrete material in the case studies here.

The general form of equations for transportation carbon footprint is expressed as follows:

$$E_{gs}(\text{gate} - \text{to} - \text{site}) = \frac{Distance\ from\ the\ job\ site * no.of\ trips}{Vehicle\ Mileage} * Carbon\ conversion\ factor \quad (2)$$

The carbon conversion factor in the above equation is obtained from carbon emissions inventory data by the United States Environmental Protection Agency (EPA 2014). Updated emission factors are published by the EPA every year and cover a wide variety of fuel types for the United States. The other parts of the equation (2) are comprised of data derived from the BIM of the project – such as the quantity of materials extracted in the previous step for material embodied carbon is used to determine the number of trips required for transport. Also, for certain projects if the supplier information is tagged along with the BIM for various materials and assemblies, the distances can be extracted directly for the calculation. Otherwise, supplier information is usually available with the contractors or sub-contractors in different forms. Actual supplier data can also be obtained from the daily field reports filed by contractors or material managers for on-site inventory of materials. For the purpose of the case studies here, this framework has been implemented using simple Excel sheets with data linked from different sources. Depending on the practices onsite, different methods can be implemented but the basic idea of conversion to carbon footprint is as per the Equation (2).

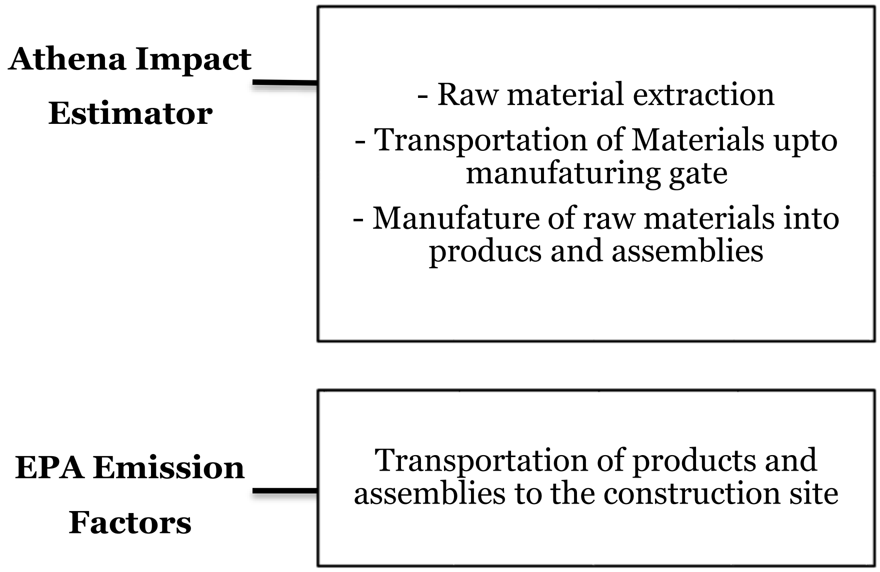


Figure 12. Embodied carbon data sources for the Model-driven measurement of Carbon Footprint

To conclude, the embodied carbon data for the materials is obtained from Athena IE and EPA emission factors. The Figure 12 summarizes the life-cycle stages and the data sources for the embodied carbon for each of the stages respectively.

4.4 Monitoring and Management Framework for Construction Carbon Footprint

Once the carbon footprint values are benchmarked, a BIM-driven framework is used for monitoring and managing actual carbon footprints. Specifically, new metrics are introduced to assess the degrees to which excessive carbon footprint (i.e. carbon footprint beyond budgeted values) are generated. Assessing the carbon-footprint actually generated is a way to increase transparency and information about actual performance of the project. A new BIM-driven visualization is also introduced to intuitively communicate the newly introduced carbon footprint metrics. Figure 6 in the method overview part shows the key elements of the monitoring and management framework.

4.4.1. Development of Carbon Footprint Management Metrics

Earned Value Analysis helps the management team assess the project performance and progress by integrating the baseline scope, cost and schedule to form the performance baseline for each work package and control account as dictated by the monitoring framework of the project (Hendrickson 2008; Project Management Institute 2013). A simple framework for time-cost monitoring as used in construction projects and the proposed carbon-footprint monitoring approach is shown in the Figure 13 which shows the synergies between the two. To explain the proposed metrics, the Earned value calculations and parameters have also been explained briefly.

In Earned Value Analysis, the variances from baseline are measured as Schedule and Cost Performance Indexes (SPI and CPI). The three parameters for the Earned value calculations are:

- Budgeted Cost of Work Scheduled (BCWS) or Planned Value (PV)
- Budgeted Cost of Work Performed (BCWP) or Earned Value (EV)
- Actual Cost of Work Performed (ACWP) or Actual Costs (AC)

The expressions for the Cost Performance Index (CPI) and Schedule Performance Index (SPI) are given in the equations (2) and (3) below:

$$CPI = \frac{EV}{AC} \qquad (3)$$

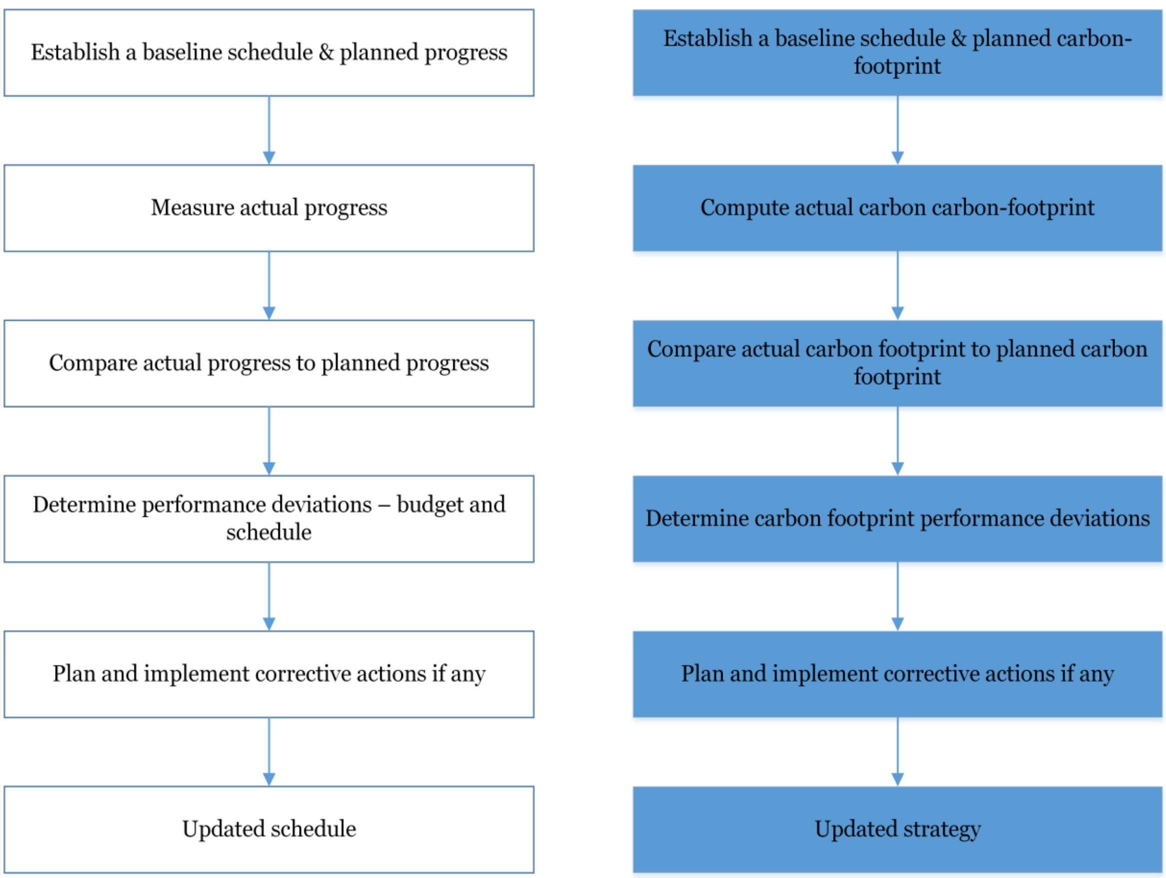


Figure 13. Synergies between time-cost construction progress monitoring and Carbon Footprint monitoring frameworks

$$SPI = \frac{EV}{PV} \quad (4)$$

The CPI and SPI are the measures of the cost efficiency and the schedule efficiency respectively and the values of the three parameters – PV, EV and AC can be monitored and reported on a periodic basis which is usually weekly or monthly. The Earned value management method is one of the most widely adopted project controls and monitoring framework used to assess and forecast project progress based on collected work-in-progress data.

Based on the framework by Memarzadeh and Golparvar-Fard (Memarzadeh and Golparvar‐Fard 2012) and drawing an analogy to Earned Value Management concepts, the following metrics are proposed and used in this study:

- Budgeted Carbon Footprint of Work Scheduled (BCFWS) as Estimated Value
- Budgeted Carbon Footprint of Work Performed (BCFWP) as Produced Value
- Actual Carbon Footprint of Work Performed (ACFWP) as Actual Cost

The carbon footprint performance can thus be measured via metrics shown in Equations 2 and 3:

$$CFPI = \frac{BCFWP}{ACFWP} \quad (5)$$

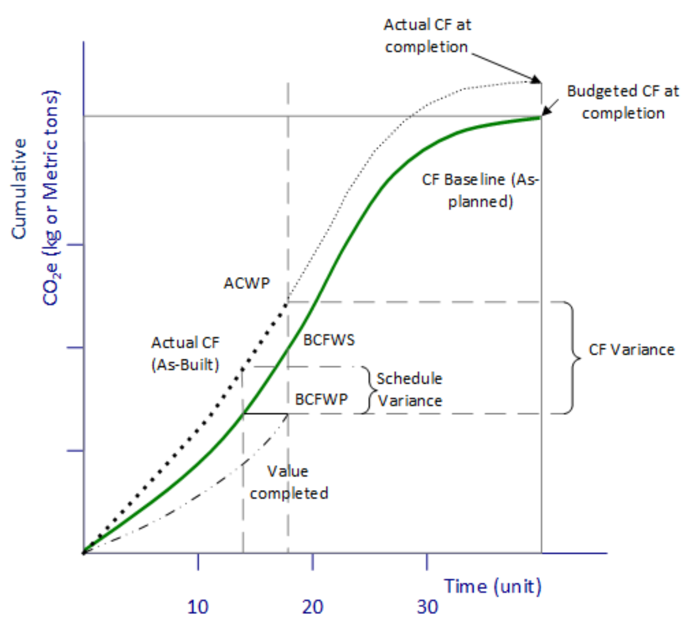


Figure 14. Earned Value, Planned Value and Actual Carbon-Footprint

$$SPI_{CF} = \frac{BCFWP}{BCFWS} \tag{6}$$

The Figure 15 adopted from Memarzadeh and Golparvar-Fard (2012) represents the Earned value analysis in terms of Carbon-footprint using S-curves to display the earned value data for a project that is exceeding its budgeted carbon-footprint and is behind schedule.

4.4.2. Interpretation of the Carbon Footprint Monitoring Metrics

The interpretation of the Carbon Footprint Monitoring Metrics defined in Equations (5) and (6) is described in detail as follows:

- $CFPI \geq 1$ shows acceptable performance, i.e. the project is not exceeding its budgeted carbon footprint value. In other words, the actual carbon footprint of the work performed is less than the baseline value of carbon footprint as per the planned work.
- $CFPI < 1$ indicates a carbon-footprint overrun for the work completed, hence unacceptable carbon-footprint performance. Thus it shows that corrective actions are required to manage the carbon footprint and bring it near or below the baseline to comply with the targeted value.
- The SPI_{CF} metric used in isolation, on the other hand, does not directly indicate whether the project is under or over its targeted carbon footprint since it only examines the schedule efficiency of the work progress. Rather it illustrates the relationship between the state of work-in-progress and the produced emission rates. Thus, it brings an additional layer of transparency and helps project teams evaluate correction strategies for the management of carbon footprint.
- If SPI_{CF} and $CFPI$ are both < 1: The progress is behind schedule and has overrun the carbon footprint baseline. This indicates the worst case scenario and reasons for increase in carbon footprint need to be investigated to mitigate the effects on project performance.
- If $SPI_{CF} > 1$ and $CFPI < 1$: The project is good on schedule but has excessive carbon footprint attributed to the progress. In this case, the SPI_{CF} shows that if strategies to reduce the carbon footprint affect the schedule, they can be

implemented as long as a severe effect on the schedule performance is not incurred.

- SPI_{CF} < 1 and $CFPI$ > 1: The project is behind schedule and is meeting the carbon footprint targets. In this case the SPI_{CF} helps project teams assess the challenges with delays in the activities while keeping in mind that the carbon footprint is still compliant with the target values.

To forecast the carbon footprint of the project based on work-packages or activity based monitoring, the Forecasted Carbon Footprint at Completion ($F_{CF}AC$) is computed. The method to calculate the $F_{CF}AC$ is based on the assumption that the rate of current carbon footprint release will continue until activity or project completion. The Budgeted carbon footprint at completion - $B_{CF}AC$ is the baseline or benchmarked value of carbon footprint which is the planned value benchmarked at the preconstruction stage. The forecasted carbon footprint at completion can be expressed as:

$$F_{CF}AC = \frac{B_{CF}AC}{CPI} \qquad (7)$$

This formulation in Equation (7) has been used in the case studies to forecast the carbon footprint at completion for different scenarios to compare with the baseline or budgeted carbon footprint value. It helps visualize the effect of current performance over the span of the activity and alert the project teams about deviations from the budgeted or target carbon footprint values. The use of this metric is more clearly demonstrated with the help of the case-studies.

4.5 Visualization of the Carbon Footprint Performance

In this model, based on the as-planned 4D BIM, a carbon footprint target is set which when exceeded, can be quickly detected and characterized through the new metrics. The targeted carbon footprint can be the benchmarked carbon footprint at completion, or a value set by regulatory requirements. The to-date as-built or actual carbon footprint released can be used to demonstrate the carbon-footprint performance based on the metrics SPI_{CF} , $CFPI$ and $F_{CF}AC$. The approach to visualizing the progress deviations in the BIM environment or n-dimensional augmented reality (D_NAR) has been presented for the purpose of construction site progress monitoring with the help of photographs and as-built model registration on BIM in several studies by Golparvar ‐ Fard and Peña ‐ Mora (2007) and Golparvar ‐ Fard et al. (2009, 2012). These methods facilitate the early detection of existing or potential delays in progress and help with root cause assessment by clearly depicting the areas affected by delays. The use of similar visualization methods has been discussed for construction carbon footprint monitoring in Ahn et al. (2013) and Memarzadeh and Golparvar‐Fard (2012).

As detailed in the interpretation of the SPI_{CF} and $CFPI$ values, the schedule and carbon footprint efficiency of the progress to-date can be gauged. The color coding is chosen to be very simple and intuitive, emulating the traffic light colors – red, yellow and green. The color Red will indicate a poor performance in both schedule and carbon footprint, ie. $SPI_{CF} < 1$ and $CFPI < 1$ to alert the project team to recognize the work-packages or activities with an unacceptable performance. The color Green indicates good performance and is simulated when $SPI_{CF} \geq 1$ and $CFPI \geq 1$, showing that the to-date progress of the work packages is under its benchmarked value and the progress is on schedule. The scenario where either the SPI_{CF} or the $CFPI$ is < 1, one of the two indices indicate unacceptable performance is coded with the color yellow, to indicate caution to the team because the project is either affected by carbon footprint overrun or is behind on schedule. This will give the team to define their problem and work towards bringing the project performance on track in both metrics.

The color coding palette based on the schemes described above has been shown in the Table 1 and Figure 16.

Table 1. Color coding palette for the visualization of carbon footprint performance

Color	$CFPI$	SPI_{CF}
Green	≥ 1	≥ 1
Yellow	> 1	< 1
Yellow	< 1	> 1
Red	< 1	< 1

If the SPI_{CF} and $CFPI$ values are represented on a graph with its origin at (1,1) since both values being 1 means the project is on-time and on-benchmarked carbon footprint, a better visualization model can be represented for the color coding. This color coding scheme can be further refined by including gradients in it, but that requires more detailed breakdown of the carbon footprint monitoring metrics to classify in varying levels of the colors. This scheme is shown with the help of the following figure (Figure 16) for the radial gradient based method for

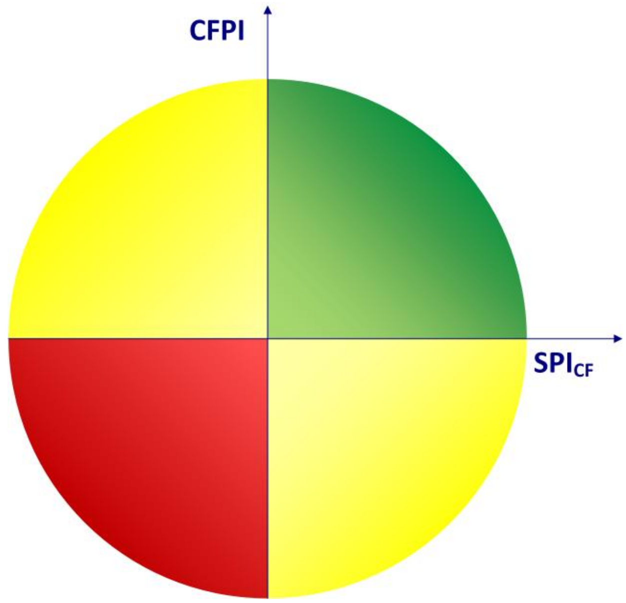


Figure 15. Color Coding Gradient for different values of SPI_{CF} and $CFPI$ in a graphical scheme

values of SPI_{CF} and $CFPI$. For the development of this test model and for simplicity, the color coding has been restricted to the template shown in Table 1.

Integration of these metrics with the 4D BIM allows carbon-footprint performance deviations to be visualized and easily communicated with the project stakeholders. Specifically, it allows project participants to easily detect what work-packages have resulted in excessive carbon footprint and take timely corrective actions that can minimize the carbon footprint associated with upcoming operations. The application of each of these aspects is described in detail for the case studies here by reflecting the color coding in the 4D BIM of the projects.

CHAPTER 5: CASE STUDIES

This chapter deals with the case-studies conducted for the validation and development of the model-driven carbon footprint management method by using actual construction projects as test cases to implement the proposed framework. The chapter begins with a description of the projects followed by the components of the method applied to the projects and presents the results of various scenarios analyzed. The projects varied in their methods and level of BIM adoption and this turned out to be an interesting factor differentiating the implementation of the BIM-driven method as is demonstrated in the case studies.

5.1 General Information

Two case-studies have been carried out for the purpose of validating the proposed method. The two construction projects have different project delivery methods and different level of BIM adoption in the project.

Project 1 - RH:

Project 1 is a 155,000 sq.ft. Residence Hall **(**referred to as **RH** henceforth) facility under construction at the University of Illinois, Urbana-Champaign. The 504 bed facility will seek at a minimum - LEED Gold Certification and comes with many state of the art facilities for students. An LoD400 BIM is developed by the construction management company and is integrated with a third-level contractor schedule for this project.

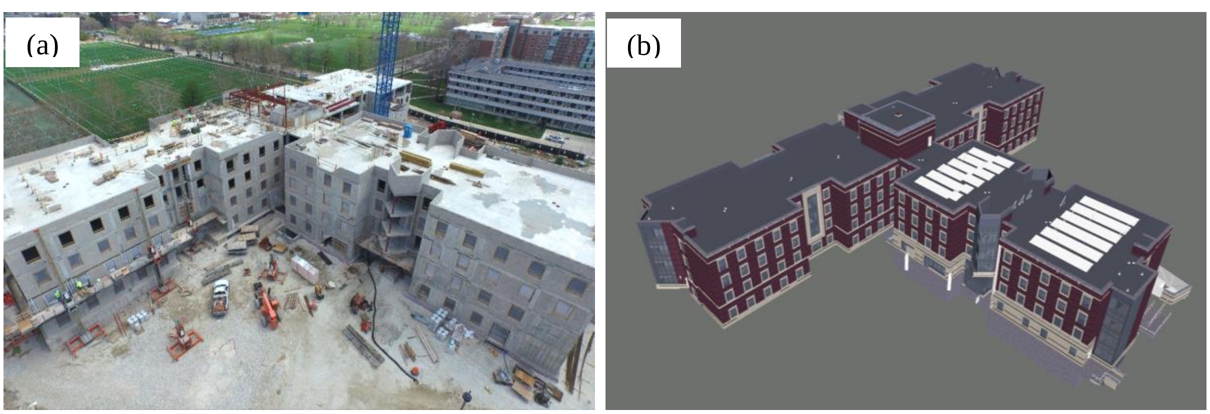


Figure 16. Residence Hall project on UIUC campus – (a) Picture from Camera-equipped UAVs used for capturing images on site (b) Image showing the BIM model in Revit Architecture

Project 2 - CB:

Project 2 is a 245,000 sq. ft. campus research building (referred to as **CB** henceforth) in Arizona with a design-build fast-track delivery process. For this project as well, a LoD400 BIM is developed by the construction company along with a Level 4 schedule. Also, more data is available in terms of resource and task assignments with the use of several workflow management and lean construction planning tools used in the project such as Assemble, BIM 360 Plan and VICO 5D. The availability of extensive information integrated with BIM helped in the efficient applicability of this model.

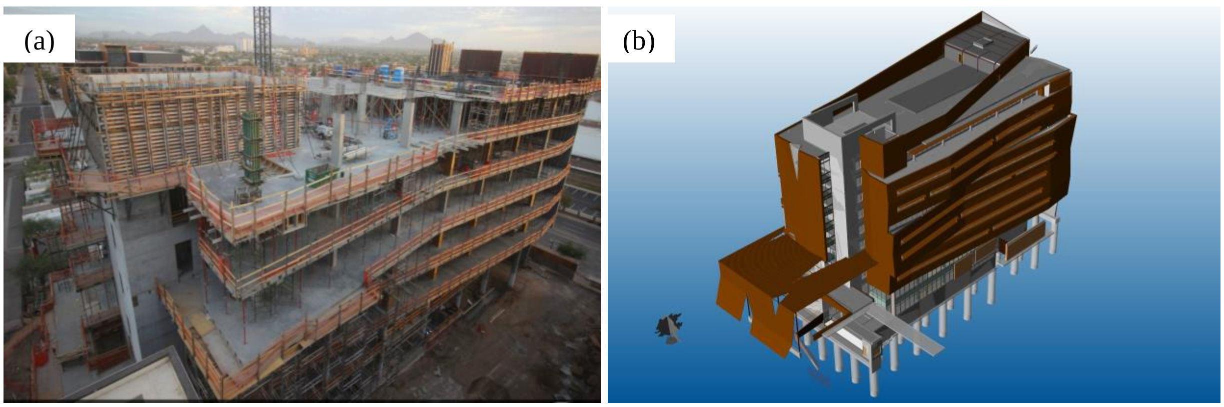


Figure 17. Biosciences Partnership Building – (a) Picture taken from camera installed on site showing the construction progress as of 11/26/2015 (b) Image showing the 4D BIM for the complete building

5.1.1. Data Collection

The data collection for both the projects varies according to the availability of the data and the scope of the projects. In general, the data collection could span across the items listed in the Table 2. Not all of this data is collected or is available in all projects. For the RH project, the data gathered was in the form of a LoD 400 BIM model in Revit and site photographs. Schedule was available in another software called SureTrak which was transferred to Primavera P6 using necessary file conversions. A 4D simulation for the project was created for the structural elements to get a better understanding of the as-planned construction progress using Navisworks and the P6 schedule. The schedule was a Level-3 schedule giving the critical activities and key milestones of the project. For developing the scenarios, some assumptions on the detailed schedule and progress of activities have been made.

The CB project from the Arizona research building provided more data apart from the LoD400 BIM and P6 based schedule. The BIM was enhanced by utility tools like Assemble which provides easy access to BIM data using a web-based platform. Also, the availability of a Level 4 schedule which gave information about the weekly work plans and look ahead schedule was very useful for the case study. The BIM 360 Plan platform used for the lean construction planning for the CB project provided information to detailed weekly activities planned for the project. It was also used to record progress and reasons for delays using root cause assessment. This is particularly helpful for implementation of such a method because it adds transparency to the project and helps assess disruptive events that might be leading to delays and increased carbon footprints of projects.

Main causes of delay as recorded in the CB project were summarized in the BIM 360 Plan platform which shows that for 25% of the delay situations, the cause is Under-estimated effort, change in Workplan causes 23% of the delays whereas unavailability of material is responsible for delays 8% of the time. All three of these root causes can be linked to increased carbon footprint in the following ways as understood from general project management activity of construction sites:

- Underestimated effort: Pushes the project teams to establish quick-fix strategies to eliminate delays which might include:
    - Increasing work shifts and requiring longer equipment operation times
    - Ordering additional material such as formwork and scaffolding
    - Ordering material from other suppliers which might be located farther away from the site or material type with higher embodied energy
- Change in Workplan: This might cause teams to implement ways to have additional resources and/or changed scope or materials for the project as follows:
    - Increased material requirement from the same suppliers
    - Increased material requirement with change in material suppliers
    - Increased equipment operation hours
- Material not available: Material unavailability may lead the team towards:
    - Procuring from suppliers which may be farther from the job site
    - Addition of suppliers with higher embodied energy materials

Material vendor selection is primarily based on the parameters of price, lead-time, supplier performance and preferred suppliers (Aretoulis et al. 2010; Safa et al. 2014) and the management of materials affects the project schedule. Carbon footprint is another parameter that the contactors and project teams should be encouraged to consider for supplier selection. As seen from the above analysis of root causes, delay in work, change orders, change in material suppliers and other disruptive events may lead to increased carbon footprint of the project. These effects will be observed by calculations for the various scenarios in both RH and CB case studies.

For the purpose of developing this case study, we focused on major concrete placement activities because (a) concrete is one of the most widely used construction materials and tasks

Table 2. Data collection sources and tools for the case studies

Type of data	Source / Tools used
3D Building Information Model (BIM)	Revit Assemble
4D Model	Navisworks VICO
Master Schedule and subcontractor schedule (as applicable)	Primavera P6
Updated schedules reflecting changes during construction	Primavera P6
Construction work-in-progress documentation	Reports from contractors
Photographs	Onsite capture using UAVs (drones) OxBlue installed camera
Daily site reports	Field Engineer
Production trending reports	Excel sheet forms by Project Engineer
Lean construction planning software	BIM 360 Plan
Weekly work plans	BIM 360 Plan
Contractor submittals	Subcontractor reporting
Project specifications documents	Contractor documentation
Supplier information	Contractor and subcontractors
Documentation of changes and/or delays in progress	Project Engineer reporting Reporting using BIM 360

associated with its placement are often repeating and (b) several studies have shown that concrete and steel are the most embodied energy and cost intensive activities during construction (Asif et al. 2007; Hong et al. 2015; Morrin 2010). Formwork has also been included in the assessments because it constitutes between 35-60% of the total cost of concrete placement activity and there is a huge opportunity for cost and carbon emissions savings in its proper selection (Hanna et al. 1992). The method described evaluates the embodied carbon of the material at both pre-construction and construction phase. Coupled with the existing parameters for suppliers and material selection, the contractors and project managers can make an informed decision for the selection of the most optimal supplier and strategy to keep the carbon emissions in check. The material procurement alternatives for concrete, steel and formwork based on the location of the site and considered various scenarios for concrete placement activities.

5.2 Case Study 1: RH

This section deals with the implementation of the model-driven carbon footprint management method for the Residence Hall (RH) project.

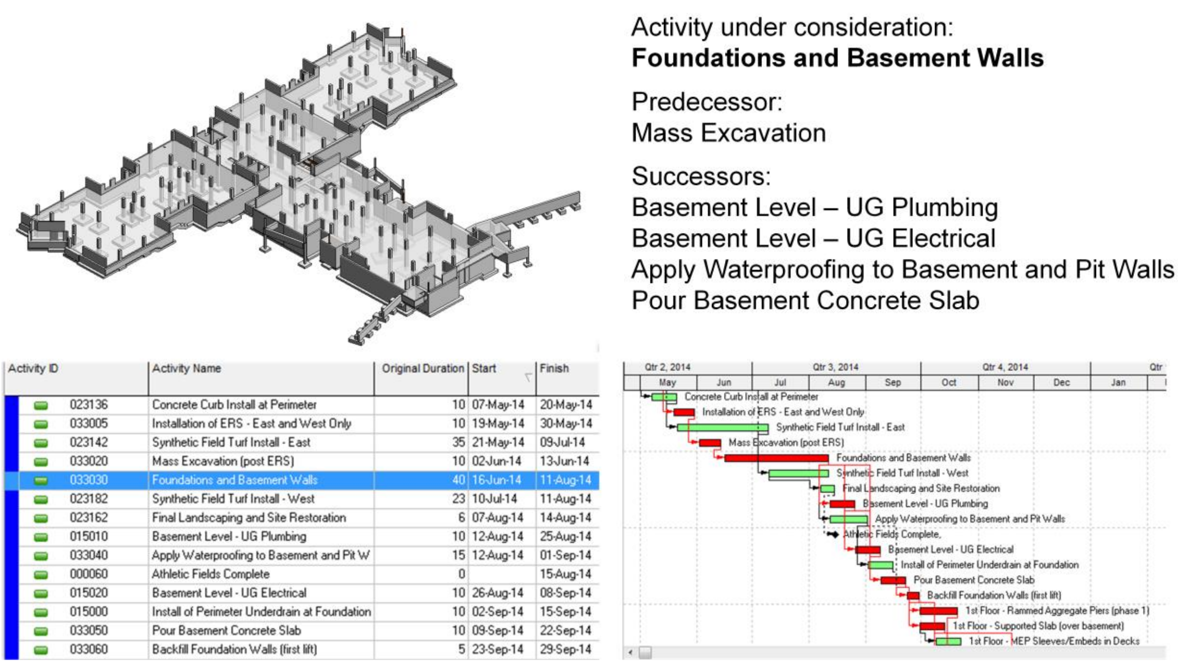
5.2.1. Specifications and Assumptions

The concrete placement activities are being considered for this study. For the RH project, some of the specifications have been delineated here. These have been either stated from the project documents and BIM that was available or have been assumed based on common project information. The concrete placement activity that is being considered for the RH project is the Foundations and Basement Walls construction. An image showing the basement level elements in the BIM and the corresponding master schedule is shown in Figure 18.

Based on the schedule, the Basement and foundation walls activity is scheduled to occur for 40 days. The supplier alternatives for the materials have been speculated based on the location of the project and using available specifications information from the BIM. The concrete on site is procured from Ready mix concrete batching plants, so the plants and their distances have been recorded. Similarly, steel and formwork suppliers and their locations have been recorded for comparing alternatives at the pre-construction stage. Some of the data and assumptions for the case study have been listed here:

- Quantities of material used for each is queried from the BIM by creating schedules and Bill of materials

- Concrete is procured from Ready mix concrete batching plants, not more than 90 minutes' travel time away from the job site
- The original supplier and material information for concrete material has been used for the benchmarking or setting the baseline carbon footprint
- The data for the capacity of concrete mixers and fuel usage is obtained from the NRMCA report on North American average data (Hinkle et al. 2014) as described in the methods section.
- For rebar and formwork, the transportation fuel usage is calculated based on average tonnage capacity of trailer trucks
- All vehicles are assumed to be gasoline fueled and no other fuel type is considered.
- The installation and construction methods used in all scenarios is the same, so that the effect of material choice alone during construction can be fully realized.



Activity ID	Activity Name	Original Duration	Start	Finish
023136	Concrete Curb Install at Perimeter	10	07-May-14	20-May-14
033005	Installation of ERS - East and West Only	10	19-May-14	30-May-14
023142	Synthetic Field Turf Install - East	35	21-May-14	09-Jul-14
033020	Mass Excavation (post ERS)	10	02-Jun-14	13-Jun-14
033030	Foundations and Basement Walls	40	16-Jun-14	11-Aug-14
023182	Synthetic Field Turf Install - West	23	10-Jul-14	11-Aug-14
023162	Final Landscaping and Site Restoration	6	07-Aug-14	14-Aug-14
015010	Basement Level - UG Plumbing	10	12-Aug-14	25-Aug-14
033040	Apply Waterproofing to Basement and Pit W	15	12-Aug-14	01-Sep-14
000060	Athletic Fields Complete	0		15-Aug-14
015020	Basement Level - UG Electrical	10	26-Aug-14	08-Sep-14
015000	Install of Perimeter Underdrain at Foundation	10	02-Sep-14	15-Sep-14
033050	Pour Basement Concrete Slab	10	09-Sep-14	22-Sep-14
033060	Backfill Foundation Walls (first lift)	5	23-Sep-14	29-Sep-14

Figure 18. Schedule and construction sequence for the Basement and Foundation walls activity for the RH project

5.2.2. Preconstruction and Material Supplier Selection

Upon availability of the supplier information, the cradle-to-site carbon footprint for concrete can be estimated at the pre-construction stage as explained in the method for computing the embodied carbon. For each of the materials in consideration here, the embodied carbon comparison between suppliers is shown and a trade-off with cost is also considered to aid the project teams in the process of choosing suppliers.

- **Concrete**

For this site, a 20 MPa (3000 psi) 35% flyash mix concrete approved as per the specifications in the contract document is procured from Supplier A. The baseline carbon footprint for the concrete placement activity of the basement and foundation walls is computed based on this mix and the supplier specified. After extracting the quantity of the material from the BIM, the bill of materials is imported to the LCA tool Athena Impact Estimator (IE) and the correct material is mapped in its interface. As seen in the methods (4.3.1) the Manufacturing stage results only are chosen from the generated Life cycle impacts report per life cycle stage. To add the carbon footprint due to transportation, the calculation is performed according to Equation (2).

The Figure 19 shows the steps used to import the Bill of Materials to the Athena IE. This includes all three materials under consideration – concrete, steel and formwork together. Figure 20 shows the method to add each material individually as an extra basic material. It can be mapped to the correct material type in the same way as for the bill of materials import. A simplified and concise Bill of Materials in Excel format was created from the original BOM file exported from Revit to simplify the import process in the IE. As seen in Figure 19 (a), the IE recognizes the header rows once the Excel / CSV file is loaded. It can be viewed to check and make required changes in the header and data rows. The IE only requires Material name, quantity and its unit of measure (UOM) to perform the calculation. So these three columns are shown mapped automatically since the column header matched the names by IE in Figure 19(b). the data rows are mapped to the correct material and unit of measure with required corrections applied as seen in Figure 19(c).

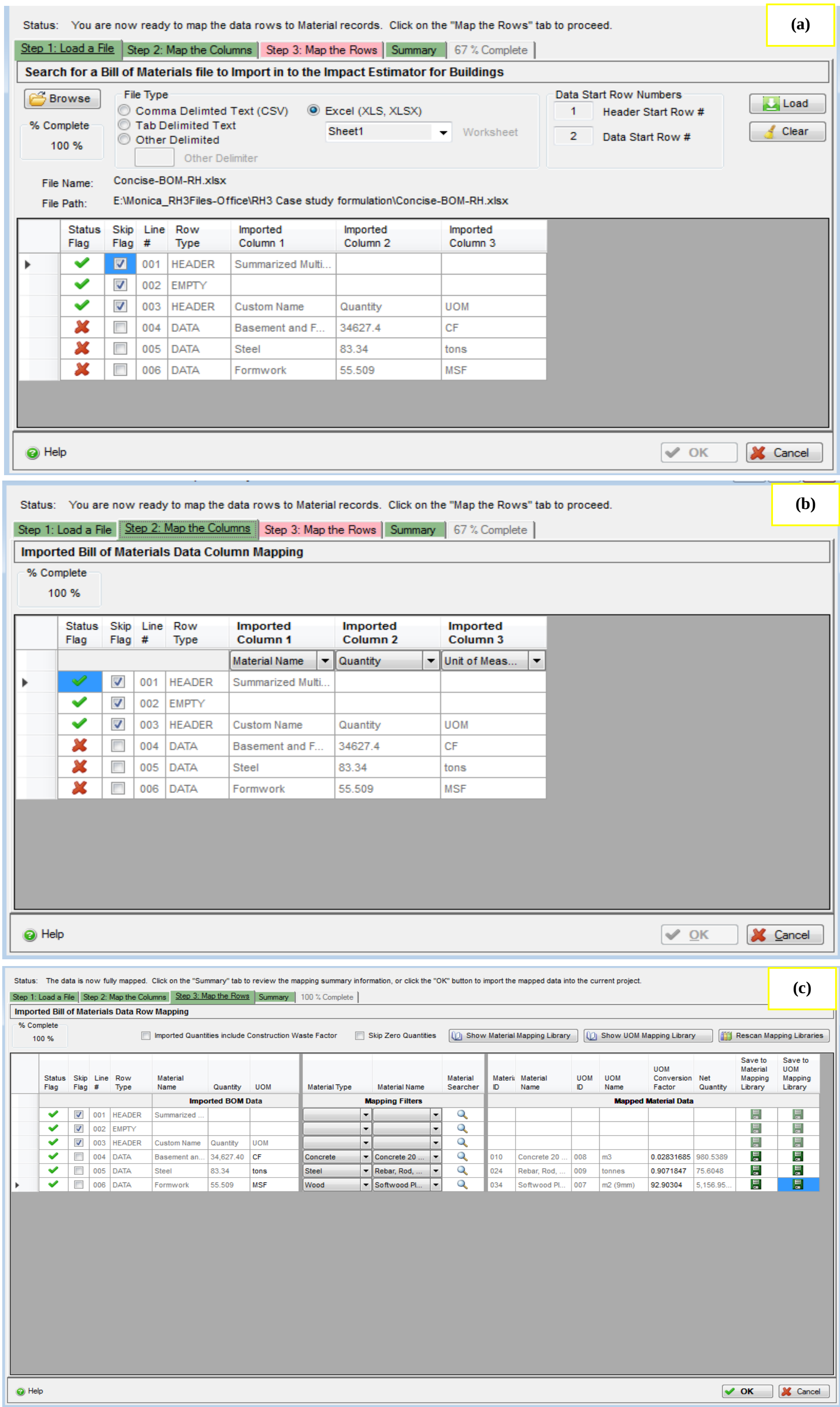


Figure 19. (a) Loading a Bill of Materials (BOM) file in IE (b) Mapping the columns to extract data from the BOM (c) Mapping the rows containing data to the correct material type from the database and applying unit corrections if required

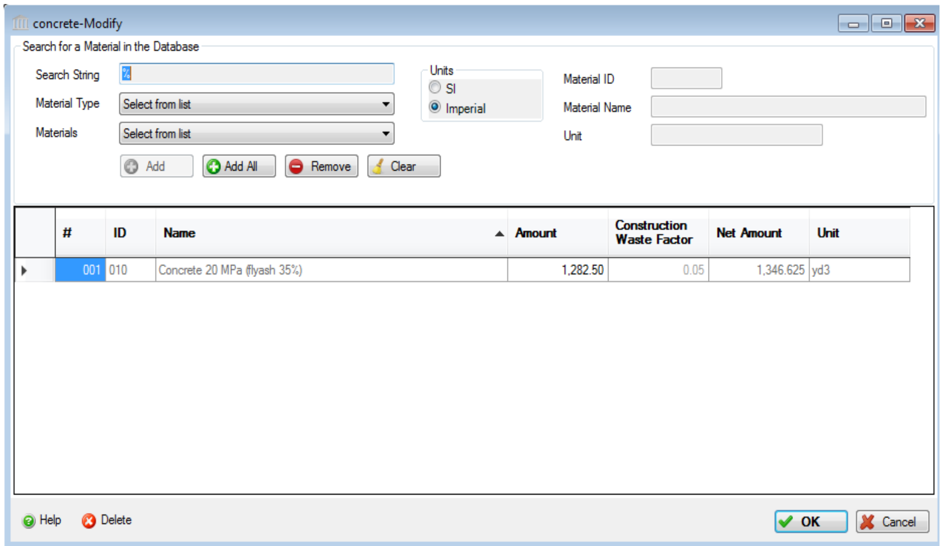


Figure 20. Adding materials manually as Extra basic materials in IE

A step-by-step calculation for Concrete material as an example, is described below:

- Material: 20 MPa (3000 psi) Concrete with 35% Fly ash replacement
- Quantity as extracted from the BIM = 1282.5 CY

Conversion of the quantities to a mass unit in SI system is not required since the IE has capabilities to perform that conversion implicitly.

The life-cycle stage impacts report from IE indicates the Cradle-to-gate embodied carbon footprint as **175379.12 kg CO_2e**

- Capacity of the mixer truck, from the NRMCA Fleet benchmarking and Costs Survey report = 9 CY

Number of trips required for given quantity = 1282.5/9 = 143

- Mileage of a truck-mixer, from NRMCA (Hinkle et al. 2014) = 3.32 mpg (miles per gallon)

CO_2 emission per gallon of gasoline for mobile vehicle sources, from EPA Emission Factors for Greenhouse Gas Inventories (EPA 2014) = 8.78 kg CO_2e

Using Equation (2), the gate-to-site embodied carbon is computed as follows:

$$E_{gs}(\text{gate} - \text{to} - \text{site}) = \frac{7 * 143}{3.32} * 8.78 = 5469.98\ kg\ CO_2e$$

Using Equation (1), adding up the embodied carbon values to get the total Cradle-to-Site Embodied Carbon we get:

$E_{cs} = 180849\ kg\ CO_2e$ ***- Benchmarked / Baseline Carbon Footprint***

This value of the embodied carbon is used as the baseline carbon representing the maximum carbon footprint level permitted for this activity. During construction, a scenario is assumed wherein the original supplier A experiences an unexpected breakdown and the project team is no longer able to procure material from this supplier. Disruptive events such as

Table 3. Concrete Supplier Alternatives for the RH Project

Alternative No.	Concrete Mix	Distance to jobsite (miles)	Price per CY
A	20 MPA, 35% Fly ash	7	101.04
B	20 MPA, no Fly ash	3.1	97
C	20 MPA, 35% fly ash	16.9	98.54
D	20 MPA, 25% Fly ash	3.9	99.5

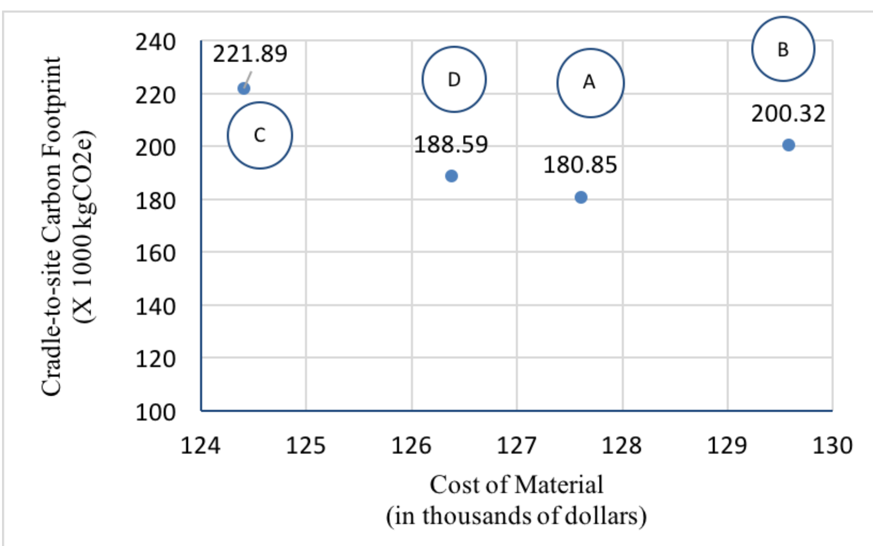


Figure 21. Carbon footprint vs. Cost of Concrete for given supplier alternatives for the RH project

shortages, untimely delivery and improper quality of material are common in construction projects. In such events, the project team members usually look at the other supplier choices available - generally from own database, and make a decision to procure material from other available alternatives. Based on the location of this site, information about prices and compliant mixes for a few available ready-mixed concrete supplier alternatives were collected and the material and transportation embodied carbon footprint were also calculated, similar to the calculation method described above. The calculation is executed in a simple Excel sheet format after using the BIM for quantity and material types and Athena for the embodied carbon calculation. For each of the material types from the suppliers A to D, the same total quantity as extracted from the BIM was used as an input in the Athena IE and it is evident that an increase in recycled material such as Fly-ash in this case reduces the embodied carbon value of the material. There was no other available composition choices in the tool for including silica fumes or blast furnace slag in the concrete but as the databases mature and expand to cover variations in materials, the same method can be used to evaluate the embodied carbon of the different material options available. The Figure 21 shows the Cost vs. Cradle-to-site carbon footprints for the material alternatives for concrete listed in Table 3.

Here, the actual supplier A which is no longer available has been included to show the comparison with the remaining alternatives in the graph. The graph suggests that for a very little increase in cost, the supplier D should be the preferable choice when A is no longer available because it has a lower value of E_{cs}. In the absence of this information, the material supplier with the least cost would have been chosen which is the alternative C in the figure and has the highest value of E_{cs}. The contractors can make an informed decision by looking at the trade-off between the cost and the carbon footprint using this method.

- **<u>Rebar</u>**

The total quantity of rebar required for the basement and foundation work amounts to 83.34 tons. The rebar on site is generally ordered in larger quantities at once before construction begins. Hence, the rebar supplier alternatives are only compared at the preconstruction stage. Table 4 shows the three rebar supplier alternatives that have been considered for this site with their prices and distance from the jobsite. In many cases, rebar is procured from farther away suppliers located in China or other countries which requires over-sea transportation. The

Table 4. Rebar supplier alternatives for the RH project

Alternative	Distance to jobsite (miles)	Price per ton ($)
E	46.1	950
F	250.0	880
G	138.0	990

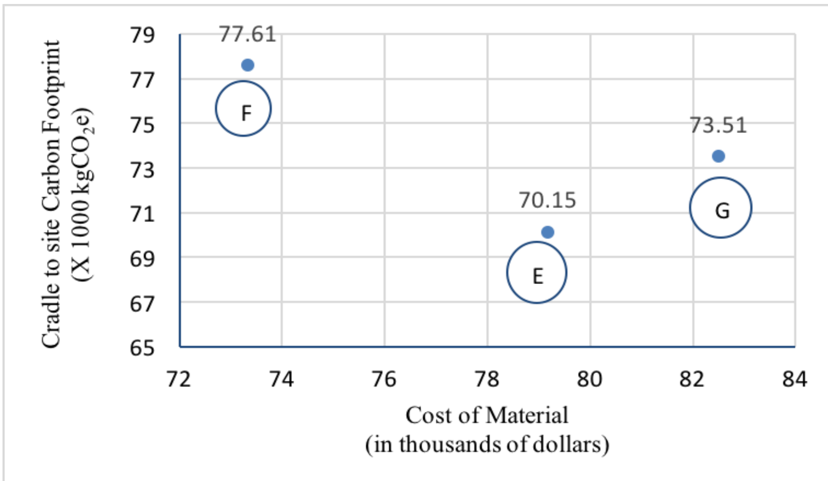


Figure 22. Carbon footprint vs. Cost of Rebar for given supplier alternatives for the RH project

transportation carbon footprint is considerably higher in that case and such a scenario analysis can demonstrate the increase in carbon-footprint and the trade-offs between cost and increased environmental impact.

It can be seen from the Figure 22 that for rebar, transportation has more influence on the total embodied carbon. The type of rebar considered here is the same from all suppliers to demonstrate the trade-off between costs and emissions due to transportation of rebar over longer distances. With the cost and cradle-to-site carbon footprint comparison in place, the contractors can insist on choosing suppliers with a lesser environmental impact. From the Figure 22, the lowest cost supplier F would not be chosen if there is a carbon cap target in place for the project. Since exceeding the carbon cap would ideally result in a penalty costing the project negatively, the objective of keeping carbon footprint in check can be realized.

Another variation in the rebar procurement can be in terms of steel with different recycled content used in manufacturing. The recycled content used in this scenario analyses was based on US average for steel manufacturing. If specific data on recycled material used is available from the suppliers that can be incorporated in the analysis and will act as another parameter that affects the total embodied carbon of the rebar.

- **Formwork**

For the RH project, two formwork supplier alternatives were compared. One of the challenges for performing the embodied carbon analysis for formwork was to find the exact type of material in the LCA tool. The IE only has softwood lumber and softwood plywood of predefined thickness values in its database. Such challenges were found in most other tools as well. The idea of comparing suppliers is simply to demonstrate the impact of variation in materials and long distance shipping of forms. For instance, if metal forms are used on site, the embodied carbon will be much higher - but the reusability of the form will also be higher. Sufficient information from suppliers to capture the data such as number of reuses and material types as well as LCA databases that can compute the embodied carbon for these materials would help establish comparisons between suppliers at the pre-construction stage. In this case, two form

Table 5. Formwork supplier alternatives for the RH Project

Alternative	Distance to jobsite (miles)	Price per sqft ($)
P	3.2	3.5
Q	119.0	3.25

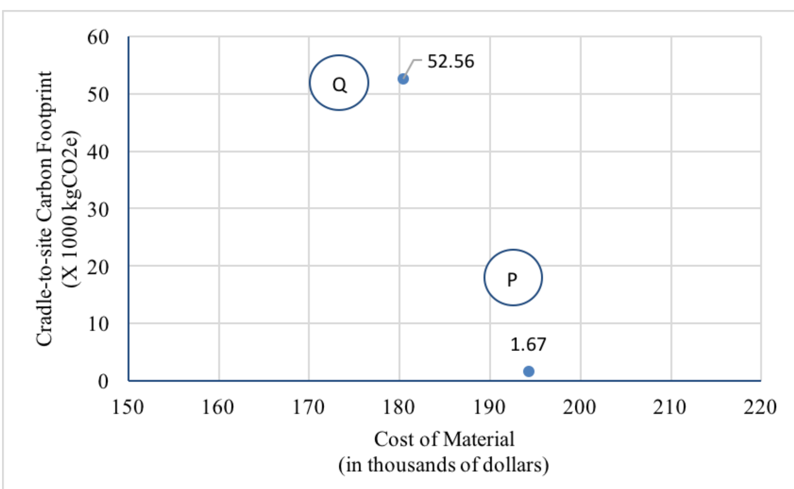


Figure 23. Carbon footprint vs. Cost of Forms for given supplier alternatives for the RH project

alternatives from different distances have been analyzed and the alternatives have been shown in Table 5.

Form re-use on site is a common practice that not only saves cost but also reduces environmental impacts. The scenario analyzed for formwork is for the situation where the forms to be reused from other work-package have not been made available because of a delay in that work package. The contractor faces the situation of either procuring new formwork from a supplier or waiting for the stripping of forms from the previous completed activity. This scenario requires the analysis of the trade-off between whether available float between activities allows for delaying the activity with minimum impact to the schedule and the cost of increased carbon footprint by ordering new material. If a cap-and-trade program is present, the direct effect of additional material induced carbon-footprint can be realized in economic overhead or added penalty costs.

Table 5 and Figure 23 show that carbon footprint of formwork significantly increases over longer distances. With this method in place, the choice of supplier P should be made at pre-construction stage. This additional embodied carbon can also be avoided by re-using formwork on site during construction. At the pre-construction stage, this method can help visualize the cost-vs.-carbon footprint trade-off for the material procurement.

5.2.3. Implementation of the Monitoring and Visualization Framework

To monitor the carbon footprint of the concrete placement activity during construction, the earned value management based monitoring and management framework defined in this study (Section 4.4) has been used. The baseline carbon footprint as computed at the preconstruction stage is being used as the targeted carbon footprint value for the activity.

- **Given Data and Assumptions**

The given data and assumptions for this analysis is described as follows:

1. The total quantity of concrete to be placed for the RH project during the 40-day period is 1,282 cubic yards (1,029 m^3).
2. The supplier and delivery information is same as what had been evaluated at the pre-construction stage.

Table 6. Concrete placement activity for the RH Project: Planned vs. Actual

Days	Planned Work (CY)	Actual Work (CY)	Supplier		
			Baseline	Scenario 1	Scenario 2
0	0.0	0.0	A	A	A
3	21.4	0.0	A	A	A
6	42.7	66.6	A	A	A
9	85.4	60.0	A	A	A
12	106.8	0.0	A	A	A
15	128.1	300.0	A	C	C
18	128.1	130.0	A	C	C
21	128.1	124.0	A	C	C
24	128.1	118.4	A	C	D
27	128.1	144.3	A	C	D
30	128.1	135.1	A	C	D
33	106.8	88.2	A	C	D
36	86.4	88.8	A	C	D
39	42.7	31.0	A	C	D
42	21.4	24.0	A	C	D

3. 20 MPa 35% fly ash mix from Concrete Supplier A is the originally chosen supplier for the given work.
4. Material quantity is taken from the BIM of the project as discussed previously
5. The rate of placement of concrete per day is assumed to follow an S-curve growth from the beginning of the activity to the end. Since the exact information of concrete pour quantity per day for this activity was not available, the S-curve pattern was adopted to form a firm hypothesized example (Table 6, Figure 24). This is in accordance with the usual resource and cost utilization patterns on construction projects rather than choosing a constant placement rate of concrete each day.
6. The carbon footprint or emissions due to equipment use and other construction operations have not been considered since they are not in the scope of this study, but they most certainly will have an effect on the deviations in planned carbon footprint in case of delays and such events.

Table 6 gives the information about planned and actual work and suppliers being used for the baseline and actual scenarios.

- **Discussion on the Scenarios**

A scenario has been hypothesized where the supply of concrete is obstructed due to breakdown of equipment at the Concrete Plant A which was the originally chosen supplier. In this situation, in the absence of a framework to compare the cost-vs.-embodied carbon of the supplier alternatives, it is seen in Table 6 for Scenario 1 that the contractor decides to procure concrete from supplier C which has the lowest cost but the highest embodied carbon (Figure 21). Thus, in the absence of a monitoring tool to visualize the deviation from the baseline or as-planned carbon footprint, the project's performance is poor and no corrective actions are considered. The deviation from the baseline emissions in this case is an increase of 21% which is a really significant increase caused just by change in material supplier on site for this one activity. This is shown with the red dashed line corresponding to ACWP(1) in the Figure 24 and is named as the Scenario 1.

On the other hand, if this monitoring method is being implemented, the project teams have a chance of noticing the projected increase in the carbon footprint from the baseline. If noticed early and shared during weekly review meetings, the contractor can decide to take corrective action and procure concrete from a more environmentally friendly supplier such as the supplier D in Figure 21. This situation is represented as the Scenario 2 by the green dashed line ACFWP(2) in Figure 24. In this scenario, the carbon footprint is brought to an 8% reduction from the scenario 1 projected levels. It is still higher than the baseline but with a lesser increase because based on the setup of this problem, the project team realizes and takes action on the supplier choice only a week later – by week 4. Table 6 shows the supplier changes in the two scenarios and the baseline along with the concrete placement rates for the 6 weeks for this activity. The graph in Figure 24 used data from this table.

- **Monitoring Results:**

Following are some points to summarize the scenarios represented in the explanation above and the Figure 24:

Baseline: If the material procurement went as planned, the total embodied carbon footprint E_{cs} will follow the curve Budgeted Carbon footprint of Work Performed – BCFWP, with the total accrued value as 180.8 MT CO_2e.

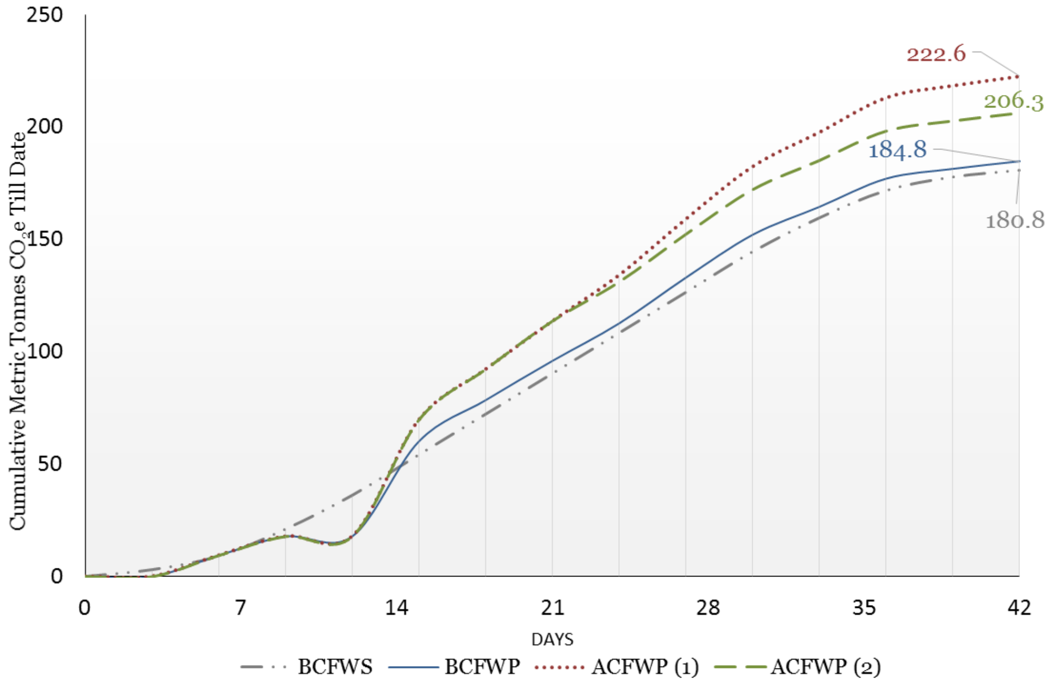


Figure 24. Carbon Footprint Monitoring – Scenario analysis for the RH project

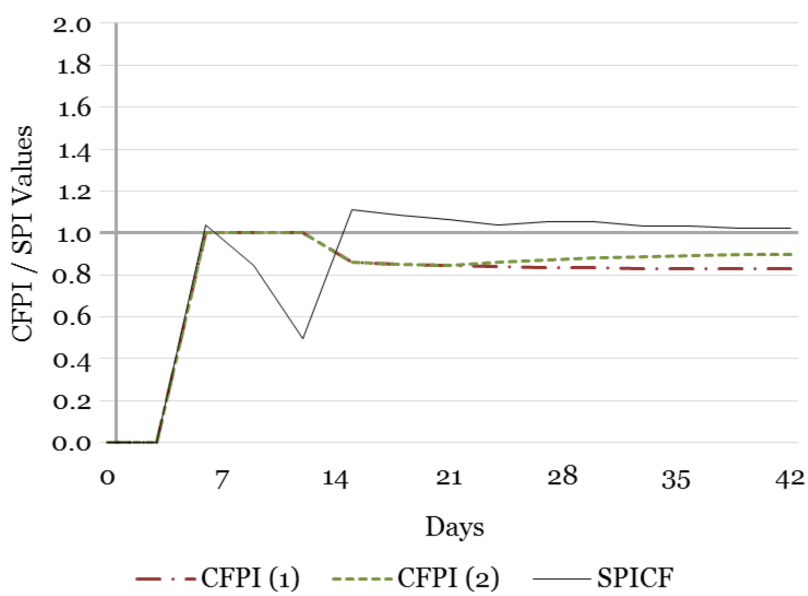


Figure 25. $CFPI$ and SPI_{CF} over the activity monitoring period for the RH Project

Scenario 1: If on the failure of supply from the Supplier A, no corrective action is taken and the Supplier C is chosen for procurement and the increase in carbon footprint is not detected in the absence of the monitoring method - the cumulative embodied carbon E_{cs} will follow the curve Actual Carbon Footprint of Work Performed (1) – ACFWP(1). This is 21% higher than the total baseline value of carbon footprint.

Scenario 2: If corrective action is taken to change the supplier to a lower embodied carbon value E_{cs} after realizing the increased carbon footprint after week 2 in the progress meeting, the scenario 2 is seen. It follows the curve Actual Carbon Footprint of Work Performed (2) – ACFWP(2). This is 12% higher than the baseline value of carbon footprint. Thus a savings of 9% is observed from just being able to identify and visualize the increase in carbon footprint from the benchmarked value by having a framework in place to measure the embodied carbon of materials.

The scenarios have also been represented in terms of carbon footprint performance index $CFPI$ and the schedule driven carbon footprint index SPI_{CF} as shown in the Figure 25. A lower value of SPI_{CF} is due to the delay in the beginning of the activity and at the end of first two weeks, it is realized that the work is behind schedule. At the end of two weeks the Actual Carbon Footprint of Work Performed increases and the CFPI becomes less than 1 because a supplier with higher E_{cs} is chosen. The $ACFWP(1)$ line represents the case where no corrective action is taken due to the monitoring framework not being implemented, i.e. Scenario 1. The $CFPI$ at the end of 6 weeks for this case is 0.83, which shows a poor carbon footprint performance. Finally, the $ACFWP(2)$ line represents the case where at the end of week 3 the project team take corrective action to change the supplier to the supplier D with a lower carbon footprint E_{cs}, i.e. Scenario 2. This brings the $CFPI$ to 0.90 – thus reducing the penalties associated with excess carbon footprint. The actual emissions are thus reduced from 222 MT CO_2e to 206 MT CO_2e, a decrease of 8% which can be significant in helping the project achieve its carbon footprint targets.

- **Visualization:**

It has been proposed that the visualization be carried out at work-package level which is already tied into the schedule. Based on the results of the monitoring framework – the values of Carbon Footprint Monitoring (CFM) metrics $CFPI$ and SPI_{CF} – the BIM is color-coded using on the color coding scheme described in Table 1.

Green – if both $CFPI \geq 1$and $SPI_{CF} \geq 1$;

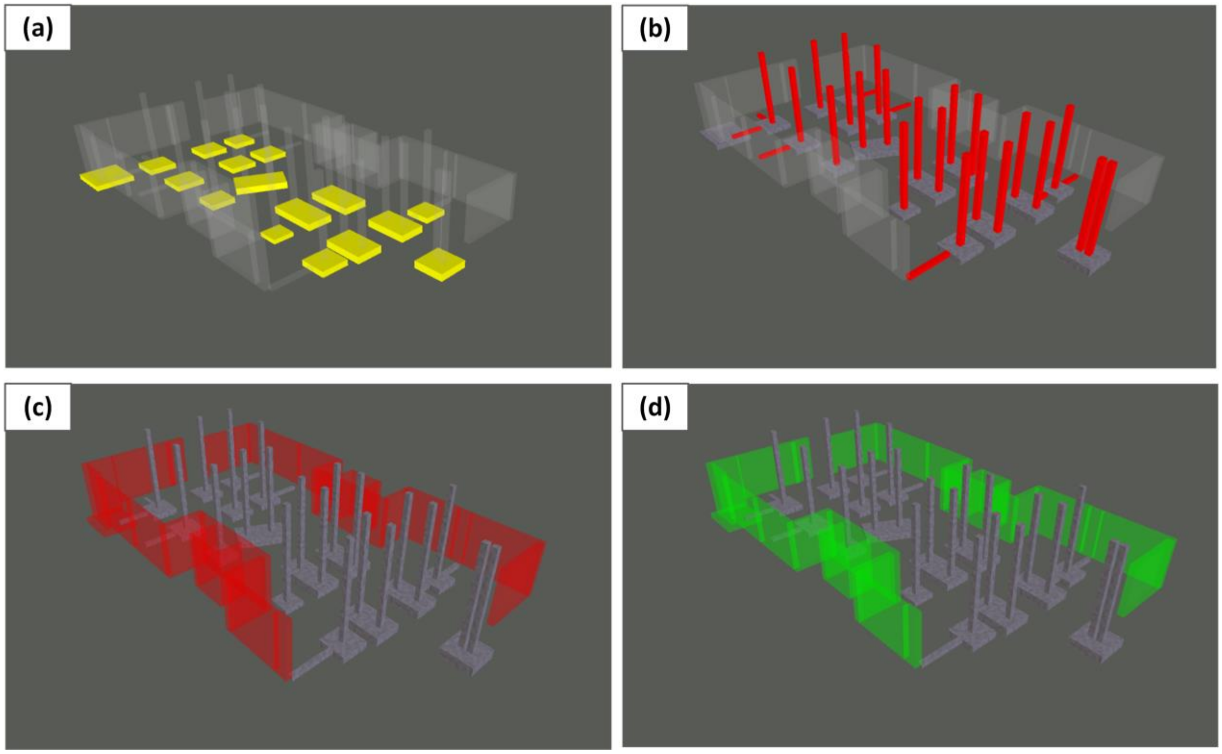


Figure 26. Visualization of carbon footprint performance of different work-packages in the Foundation and Basement walls activity for the RH project: (a) Day 8 when $CFPI$ > 1and SPI_{CF}< 1 , (b) Day 14 when $CFPI$ < 1and SPI_{CF}< 1; (c) and (d) are alternative realizations of Scenario 1 and 2 if the supplier choice is changed to a lower carbon footprint for the foundation walls work package

Yellow – if $CFPI$ > 1 and SPI_{CF}< 1 or $CFPI$ < 1 and SPI_{CF}> 1;

Red – if $CFPI$ < 1 and SPI_{CF}< 1;

Figure 26 shows the visualization for the concrete monitoring scenario and the calculated metrics. As seen in Figure 26(b) and 26(c) if the $CFPI$ falls below 1, the excess carbon footprint rates can quickly be detected and corrective actions can be planned for the future work packages to improve the overall carbon footprint performance.

One of the challenges with visualization based on work packages is the availability of weekly work plan scheduling and reporting from the site on work-in-progress. The visualization is conceptually presented here, but requires further refining and validation in actual site workflows, which was done to some extent in the next case study for the CB project.

5.3 Case Study 2: CB

This section deals with the implementation of the model-driven carbon footprint management method for the Campus Building (CB) project in Arizona.

5.3.1. Specifications and Assumptions

Similar to the RH project case study, concrete placement related activities are being considered for the BIM-driven carbon footprint management framework implementation for the CB project as well. As described previously, much more data in terms of BIM and work-in-progress monitoring is available for this project. Hence the focus for this case study was just on the monitoring and management part of the framework. Also, the use of the method at pre-construction stage has been demonstrated in the previous case study.

For the development of the analysis, three work packages from the 4th floor superstructure construction have been chosen. Figure 27 shows the structural model of the building prepared in Revit Architecture. The model highlighting the 3 work packages that have been considered is represented in Figure 28. The concrete placement of these 3 work-packages is scheduled for a total of 8 days. They have been identified as follows:

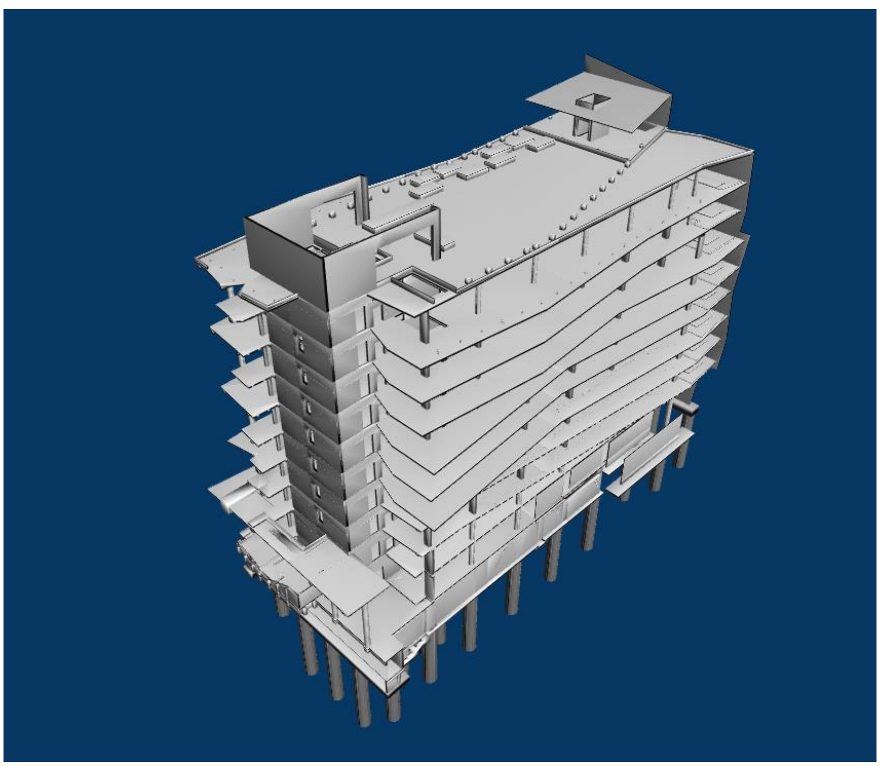


Figure 27. Concrete Structure model of the CB project prepared in Revit – picture taken from Assemble

L4-ESW: Level 4 East Shear Wall

L4-CP1: Level 4 Column Package 1

L4-CP2: Level 4 Column Package 2

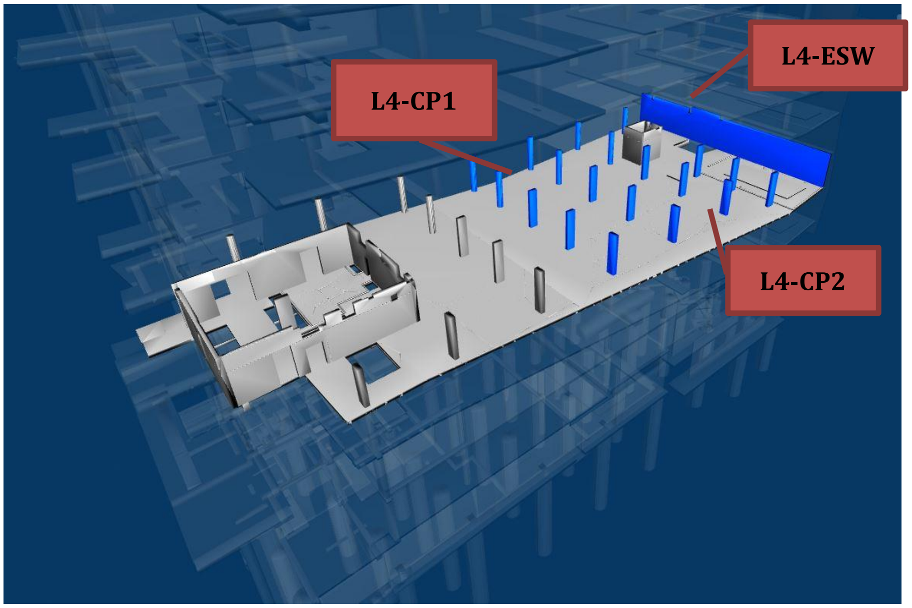


Figure 28. Highlighted elements represent the work-packages for the concrete placement activity under consideration (Picture taken from Assemble) for the CB project

Activities

Layout: Classic Schedule Layout | Filter: All Activities

Activity ID	Activity Name	Original Duration	Planned Start	Planned Finish	Actual Duration	Actual Start	Actual Finish	Total Float
CS-DPR-1 (New Project)		8	24-Aug-15	02-Sep-15	14	19-Aug-15	07-Sep-15	
A2000	L4-CP1-Rebar	2	24-Aug-15	25-Aug-15	2	31-Aug-15	01-Sep-15	
A1000	L4-ESW-Form	3	25-Aug-15	27-Aug-15	12	19-Aug-15	03-Sep-15	
A2010	L4-CP1-Forms	2	25-Aug-15	26-Aug-15	2	01-Sep-15	02-Sep-15	
A2020	L4-CP1-Pour	1	26-Aug-15	26-Aug-15	1	02-Sep-15	02-Sep-15	
A3000	L4-CP2-Rebar	2	26-Aug-15	27-Aug-15	2	01-Sep-15	02-Sep-15	
A1010	L4-ESW-Rebar	2	27-Aug-15	28-Aug-15	2	03-Sep-15	04-Sep-15	
A3010	L4-CP2-Forms	2	27-Aug-15	28-Aug-15	6	27-Aug-15	03-Sep-15	
A1020	L4-ESW-Inspection	1	28-Aug-15	28-Aug-15	1	04-Sep-15	04-Sep-15	
A3020	L4-CP2-Pour	1	28-Aug-15	28-Aug-15	1	04-Sep-15	04-Sep-15	
A1030	L4-ESW-Close	2	31-Aug-15	01-Sep-15	2	04-Sep-15	07-Sep-15	
A1040	L4-ESW-Pour	1	02-Sep-15	02-Sep-15	1	07-Sep-15	07-Sep-15	

Figure 29. As-planned and Actual start and finish dates for tasks for the three work packages for the CB roject

Some of the data and assumptions for the case study have been listed here:

- Information collected from the site includes the schedule, the BIM files of the project in Revit.
- Quantities of material used for each of the work-package is obtained from Assemble, a web-based tool which provides access to BIM data and is used for model-based estimating as well. This tool was being used by this project team for their operations and was made accessible for studies.
- Athena Impact Estimator (IE) is used for the embodied carbon calculation along with the transportation carbon footprint added to it as described in the methods section.
- The installation and construction methods used in all scenarios is the same, the effect of material choices only on the total carbon footprint is being analyzed.
- The equipment emissions due to on-site use is not being considered.

Additional information available: For the CB project, as described previously, the information collected from the site includes the schedule, weekly look-ahead planning using BIM 360 and Assemble for cost and BIM data.

5.3.2. Implementation of the Carbon-Footprint Monitoring and Visualization Framework

The three work packages under consideration were thoroughly analyzed for implementing the carbon footprint monitoring module for this case. Figure 28 shows the schedule for the three work packages with their actual start and finish dates. This was prepared in Primavera P6 from the information available for the progress reporting efforts by the team. The actual work-in-progress information is recorded in the BIM360 Plan tool which is a cloud-based lean construction planning software that can be used for pool-planning sessions and task assignment and reporting. For concrete placement activities only, the concrete production trending charts have been prepared which show the planned-vs.-actual progress for each work-package and report delays and productivity differentials. This information is very useful in analyzing the performance and understanding the root causes of the delays and incomplete deliveries. The root causes are also recorded in the BIM 360 environment, which upon further analysis in the tool gives the project-wide summary of the causes. As stated in the Data collection section of the case-study, Change in Workplan and material not being available

Table 7. Concrete supplier alternatives for the CB project

Alternative No.	Concrete Mix	Distance to jobsite (miles)	Price per CY
A	30 MPA, 25% Fly ash	5	101.04
B	30 MPA, 35% Fly ash	3.5	97
C	30 MPA, 35% fly ash	20	98.54
D	30 MPA, no Fly ash	7	99.5

constitute of over 31% of the delays and obstacles in the tasks completion as-planned. This is the underlying focus of the scenario analyzed here.

- **Scenario analysis:**

The as-planned total concrete to be poured during these 3 work packages is 102.1 cubic yards (78 cum). The material supplier choices similar to the RH case study have been evaluated for the project. Supplier A is the original supplier from which 30 MPa 25% fly ash is being procured. Other suppliers have been assumed based on the location of the site and have been summarized in the Table 7.

The following Figure 30 gives the total cradle-to-site embodied carbon (E_{cs}) values for these supplier alternatives with their cost for a comparative analysis of the most competitive supplier. The scenario formed here based on studying the causes of delay for the project is that due to change in workplan and/or material unavailability, the tasks are delayed.

The scenario is described as follows:

- Based on the actual work, concrete material is not available for the pour scheduled on 28th August.

- It wouldn't have been available for the next week so the project team decided to procure concrete from Supplier D which was available to them and proceed with the pour on September 4th.

Scenario 1: In the absence of the framework, the team doesn't realize that the carbon-footprint from Supplier D would be about 11% higher than the budgeted or baseline carbon-footprint. This would also be visualized with the help of the carbon-footprint monitoring metrics and also by color coding in the BIM of the project by the visualization method described.

Scenario 2: If the monitoring and benchmarking method is put into practice, the project managers can visualize that the carbon footprint will be negatively impacted and will choose a supplier such as B or C to reduce the overall carbon footprint. In this case, they can also see that for a very little benefit on the carbon footprint, supplier B costs a lot more.

- Also, choosing the supplier C in scenario 2 reduces the total embodied carbon impacts for these set of work packages below the baseline, giving a reduction of about 15%. This reduction can be used against some other tasks which might cause an increase in the carbon-footprint. Such an analysis is only possible if the carbon footprint is monitored and deviations are visualized.

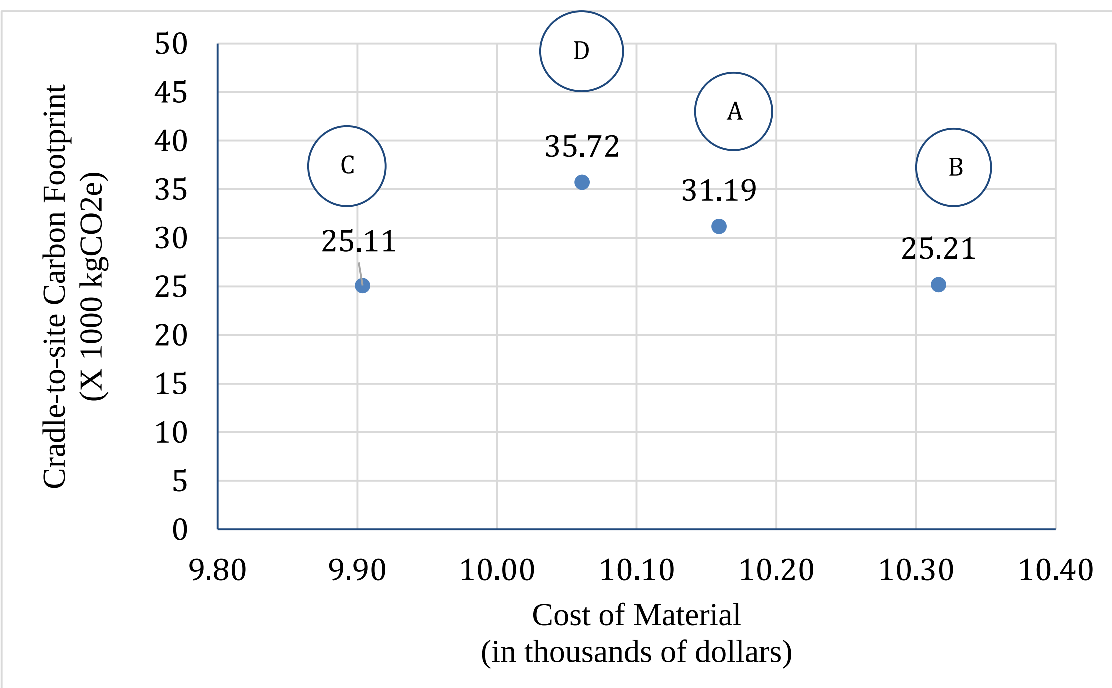


Figure 30. Cost vs. cradle to site carbon footprint of concrete suppliers for the CB project

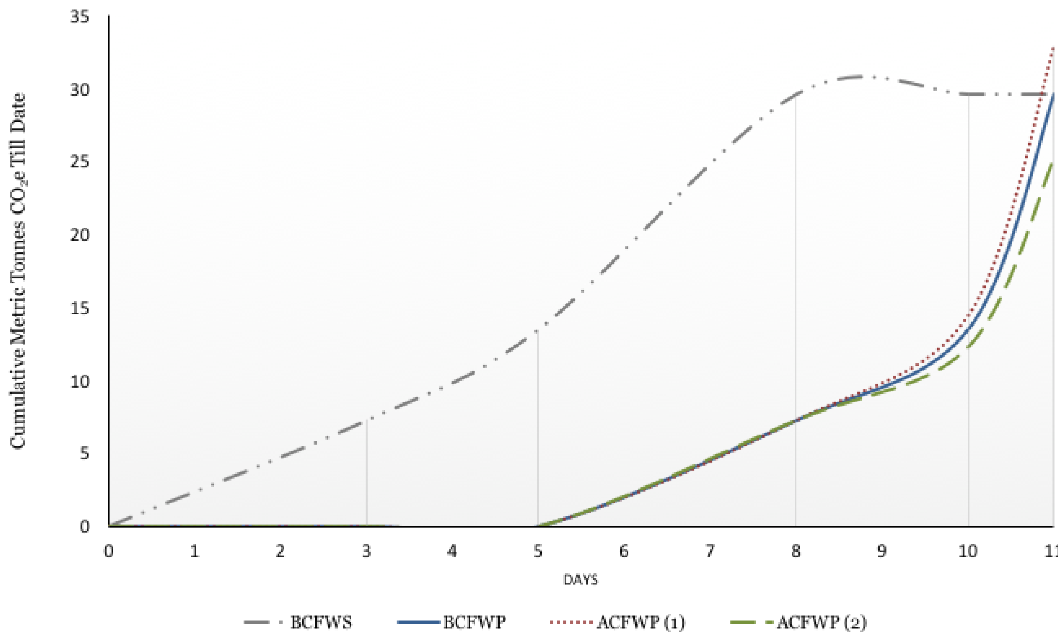


Figure 31. Carbon-Footprint monitoring for the CB Case study

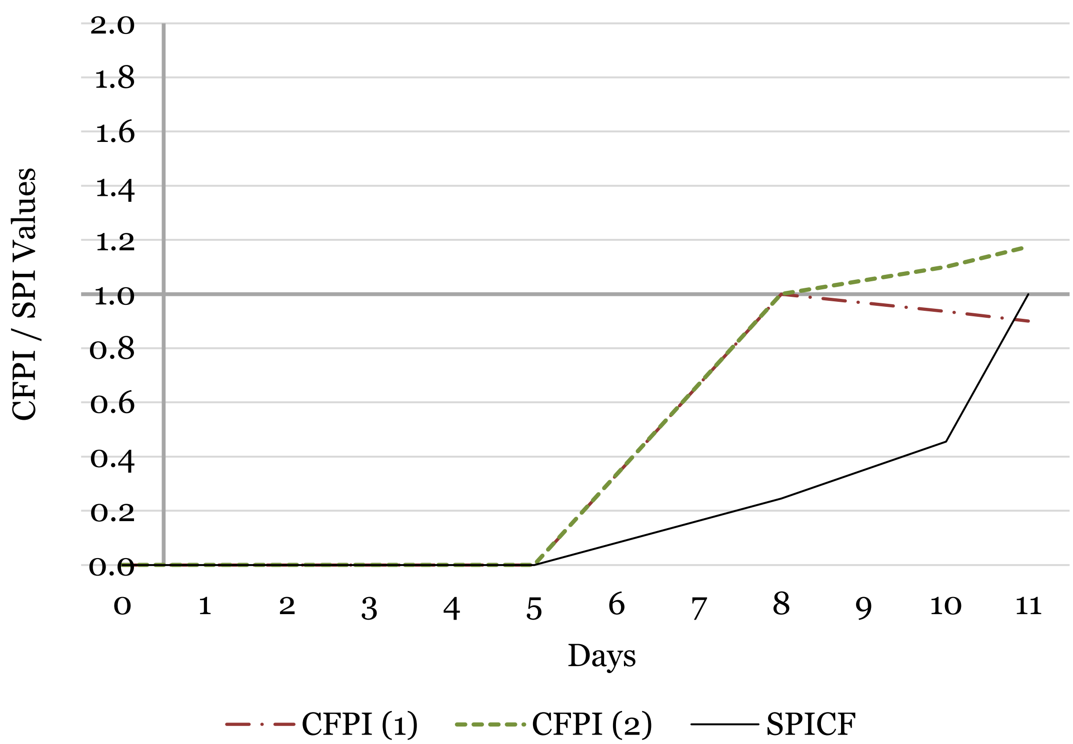


Figure 32. $CFPI$ *and* SPI_{CF} variation for the CB Case Study

- **Results and discussion**

The following Figure 31 shows the planned-vs.-actual carbon footprint accrual over the duration under consideration. The Red dotted line for the actual carbon-footprint Scenario 1 shows that it exceeds the baseline carbon footprint if no corrective action is taken. The $CFPI$ at the end of the three work packages is seen to be 0.9 and SPI_{CF} is also less than 1, which indicates poor performance. This is represented in the Figure 32.

The Green dashed line for the Scenario 2 indicates that if the supplier choice is changed, the actual carbon footprint is lower than the baseline value and there is an improvement in the carbon footprint performance. The $CFPI$ in this case is 1.17 and SPI_{CF}=1, which indicates a positive performance (Figure 32).

With the use of the monitoring tool, the project team is able to visualize the carbon footprint metrics and their performance which helps them in decision-making. As seen here, a carbon footprint savings which was plausible could have been missed by the project team in the absence of this implementation.

Another important observation from this case study was that the availability of regular work-in-progress data is very important for using this BIM driven method for analyzing the planned vs. actual carbon footprint. A consistent monitoring method throughout the project and updated schedule information is also integral to such a study. Since for this case study, this information was available in the form of various BIM tools, the analysis was clear and simple to undertake. This analysis can by further improved by adding actual supplier information with the materials and pushing for environmental product data from the supply chain to accurately account for the lifecycle embodied carbon impacts.

CHAPTER 6: CONCLUSION AND FUTURE WORK

This study presented a new BIM-driven framework for benchmarking, monitoring, and managing carbon footprint during execution of a construction project. It also validated the application of the framework with two real-world case studies. As the construction industry continues to evolve towards more sustainable practices, by using the proposed framework, construction practitioners can influence the other sectors of the supply chain by creating demand for products with low carbon processes, address carbon impact by intelligent specification and encourage the use of locally sourced and recyclable materials. Some of the important conclusions and discussion for future work follows in this section.

6.1 Conclusions

The case studies conducted here show that by the implementation of a BIM-driven monitoring and management tool for construction carbon footprint, there is a potential for preventing excessive carbon-footprint release. Results from both the case studies throw light on ways project teams can visualize the carbon-footprint and compare material and delivery choices to prevent exceeding the baseline carbon footprint.

The main conclusions and observations from this study are described as follows:

1) Making optimal material supplier choices – The framework enables the contractors and project teams to choose the best supplier that minimizes not just the cost but also the cradle-to-site embodied carbon footprint of the materials. With the use of BIM tools and the method to compute the carbon footprint of manufacturing and transportation, the contractors can visualize the supplier choices at the pre-construction stage to make the most optimal decision. The same applies for the use of this method during construction when project teams have to decide about procuring additional material due to changes in workplan or material shortages.

2) Preventing excess carbon-footprint – It was observed for both case studies that using the carbon footprint monitoring method with the help of the earned-value based metrics $CFPI$ and SPI_{CF}, contractors can detect deviations from the baseline carbon footprint in a timely manner. Once the progress deviations are known, the team can

take any corrective actions required with the help of the embodied carbon assessment method and forecast the overall performance of the activity or tasks with respect to the baseline or targeted carbon-footprint. Representation of the information about the current performance with respect to work-in-progress is key to the carbon-footprint management in projects. Apart from helping comply with the benchmarked emissions, the framework also shows opportunities for improvement of the performance which was observed in the second case study with a reduction in the total embodied carbon footprint.

3) Carbon footprint management metrics – The earned value based metrics proposed here are $CFPI$ and SPI_{CF}. The $CFPI$ (Carbon Footprint Performance Index) is modeled similar to the Cost Performance Index (CPI) and indicates the carbon-footprint efficiency of the project and a value greater than 1 shows a good performance. The SPI_{CF} (Carbon-Footprint based Schedule Performance Index) which is modeled similar to the Schedule Performance Index (SPI) indicates the schedule efficiency of the project and the relationship between the state of the work-in-progress and currently produced emission rates. This information is useful in determining what kind of corrective actions can be taken to improve the carbon footprint performance keeping in mind the schedule and timely completion of tasks to not affect the SPI_{CF} adversely.

4) The level of use of BIM and integration of BIM in the project management framework during the construction phase affects the ease of implementation of this method. The more the use of various BIM tools for construction planning and progress monitoring, the easier it is to implement the carbon-footprint monitoring method. This is because of the readily available as-planned and work-in-progress data for the calculation and integration to the LCA tools. A very negligible amount of additional data collection and swift integration with the LCA tools pushes for a higher possibility of implementing an automated workflow for carbon footprint monitoring. As seen in the case-studies here, for the CB project, since all the BIM data was easily available for the structural elements construction from the project team's use of the

right BIM tools, there was no requirement to perform extra calculations such as extracting quantities of materials from the Revit models for planned and actual work. Performing the analysis for the carbon footprint monitoring and management could be done quite easily from the data.

5) Availability of more BIM related information also leads to better visualization of the carbon-footprint by this method. Since work-in-progress information for given tasks can be obtained and is linked to the BIM of the project, the color coding for the work-packages to indicate the $CFPI$ and SPI_{CF} values is easier and thus the carbon-footprint performance of the project to date can be communicated clearly.

6) The carbon-footprint monitoring and management tool is applicable for a cap-and-trade program implemented for construction projects to regulate the carbon footprint. Since the method helps in quantification of the baseline carbon footprint and the project's actual carbon footprint, it can help implement a carbon cap based regulation wherein contractors are penalized if they exceed a certain level of emissions. The cap can be set based on the baseline carbon-footprint of as-planned work and applicable state and federal environmental regulations or benchmarked practices across industry. Similarly, another application of the proposed management framework is for establishing policies requiring adherence to a carbon footprint budget during project tendering to award contracts considering the carbon-footprint along with the cost and time.

7) Similar to cost, carbon footprint management can act as one more driver of increasing the efficiency of construction and reliability of work completion in time since delays and unforeseen disruptions often lead to excessive carbon footprint as observed in the cases studies. Carbon footprint targets will also drive the teams towards efficient planning and allocation of resources since such a framework will allow them to measure and visualize their performance. Although it is understood that monetary penalties being linked with exceeding carbon footprint might be much more effective to promote such practices.

8) Comprehensive database of construction materials should be made available to account for the changes like proportion of recycled material in concrete, steel and different variations of the same material category. The true value of embodied carbon reduction can be realized in a better way if that kind of information is captured. The implementation of this framework does provide an incentive to contractors to choose suppliers with lower environmental impact which should drive better data availability from suppliers and manufacturers.

6.2 Future Work and Applications of the Method

Further expansion of this research is expected in the form of automated carbon-footprint monitoring of projects based on this BIM-driven framework. The automated carbon-footprint management method can leverage automated vision based work-in-progress monitoring methods. Such an implementation will make the process of carbon-footprint management seamlessly integrate with the project’s monitoring framework.

Exploring the use of cap-and-trade policies for managing carbon footprint at a project-level is another application and future scope for this study. The method does have the ability to be used for a cap-and-trade regulation so further validation of such an implementation would be required. Apart from this, the scope of implementing construction focused credits in LEED rating system should be explored. This method can be used to achieve one of the Innovation credit points by demonstrating reduction in the construction phase carbon-footprint from the baseline. The same is true for the other rating systems like Envision which is for infrastructure projects and other rating systems as well.

Another important area of interest for this study can be to quantify the carbon-footprint of construction processes including equipment use on site and compare different installation and construction methods for their embodied carbon impact during construction phase.

The use of BIM for sustainable construction is a fairly new area of exploration in the construction industry. As life cycle assessments are being used increasingly for pursuing the certifications and credits from green building and infrastructure rating systems, more applications for integrating sustainable practices into construction are being envisioned. This study opens up some interesting areas of further exploration as described here.

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